WAVELENGTH SELECTION AND SWITCHING IN SHORT PULSES GENERATED FROM SEMICONDUCTOR LASERS

By

CHOW Kin Kee

A Dissertation

Submitted in partial fulfillment of the requirements

for the degree of Master of Philosophy

in

Department of Electronic Engineering

© The Chinese University of Hong Kong

July, 2000

Supervisor: Prof. Chester Shu

The Chinese University of Hong Kong holds the copyright of this thesis. Any person(s) intending to use a part or whole of the materials in the thesis in a proposed publication must seek copyright release from the Dean of the Graduate School.

香港中文大學
圖書館系統
★ ★
28 JUN 2001
UNIVERSITY
LIBRARY SYSTEM
THE CHINESE UNIVERSITY OF HONG KONG

ABSTRACT

Fast wavelength switching of short optical pulses near 1.55 μm has been successfully demonstrated. The dynamic change of the characteristics of semiconductor lasers during the switching process is also investigated.

Self-seeded dual-wavelength pulses are generated from a Fabry-Perot laser diode in an external cavity containing a two-chromatic fiber grating. Electrical switching between single-mode and dual-mode operations is demonstrated by controlling the amplitude of the ac signal applied to the laser diode. The principle is based on carrier induced frequency chirp that determines the spectral overlap of the Fabry-Perot modes with the grating reflection band during the pulse buildup time. The time required to reach the steady states is experimentally determined to be about five to six round-trip cycles. The buildup of single-mode emissions is slightly faster than that of the dual-mode.

With the mutual injection-seeding scheme, electrically wavelength-tunable pulses are generated from Fabry-Perot laser diodes at 1 GHz. By investigating the spectral dynamics we experimentally show that stable single-mode output can be obtained after four round-trip propagation cycles in the external cavity. The dynamic change of the spectrum during the switching between two single-mode wavelengths is also investigated. It is found that the steady states can be reached after six to seven round-trip cycles.

We also study the dynamics of spectral change in a distributed feedback (DFB) laser under external feedback. A simple external cavity is constructed to provide adjustable feedback to a gain-switched DFB laser diode. A 27 dB enhancement in the side-mode suppression ratio (SMSR) and a 0.3 nm reduction in the spectral linewidth have been observed. The improvement shows a saturation behavior when the feedback power reaches about -16 dBm. The dynamics of the spectral improvement has been investigated. The steady state can be achieved as soon as four round-trip feedback cycles are completed. The dependences of the speed of improvement and the SMSR on the feedback pulse arrival time are also investigated. The optimal result can be obtained over a sensitive time window of about 20 ps.

摘要

本文主要討論了1.55μm超短光脈衝源的快速波長轉換，並對半導體激光器在波長轉換過程中的動態變化特性進行了深入的討論。

基於自注入技術，並利用一雙波長光纖光柵構成外腔，成功地由FP半導體激光器得到雙波長光脈衝輸出。由於載流子濃度的改變會導致頻率啁啾，從而在脈衝建立過程中，半導體激光器的FP模與光柵反射峰的重疊狀況就會發生相應的改變，因此，通過調節加載到半導體激光器的射頻電信號的振幅就可以實現單波長與雙波長之間的轉換。實驗結果證實，光脈衝在五至六個外腔往返之後就可以得到穩定的輸出。另外，單波長脈衝的建立時間較雙波長稍短。

利用雙向注入技術，成功地從FP半導體激光器得到1GHz波長可電調諧的光脈衝。實驗證實穩定的單模震蕩可在四個外腔往返後得到。此外，對於不同波長的單模震蕩之間的轉換，穩定的光輸出需在六至七個外腔往返後得到。

最後，本文也研究了外腔光反饋對DFB半導體激光器的光譜特性的影響，實驗中通過調節增益調制半導體激光器的光反饋，發現獲得最佳實驗結果的反饋強度爲 -16dBm，成功地將鄰模抑制率改善了27dB，將譜寬也減小了0.3nm，並證明了在四個外腔往返後可得到穩定的輸出。本文還指出，反饋脈衝到達半導體激光器的時間對輸出光譜特性也有一定的影響，實驗結果表明其最佳爲20ps。

ACKNOWLEDGEMENTS

I would like to express my special thanks to my supervisor, Prof. Shu Ching Tat, Chester, for his valuable guidance, suggestions and experienced support during these years. Many thanks to Prof. H. K. Tsang, for sharing with me of his technical ideas and comments. Also, I am grateful to Prof. K. T. Chan for introducing me the basic concepts of optical communications.

I am indebted to Dr. K. S. Lee, Dr. L. Y. Chan and W. K. Mak for sharing their ideas and experimental techniques. Many thanks to Barbara Ho for her technical support in the laboratory. Also, I would like to express my sincere thanks to Fiona Tsui and my family, for their kind support during my research life.

Finally, I would like to express my appreciation to my colleagues, Dr. K. S. Lee, Dr. L. Y. Chan, W. K. Mak, K. Chan, C. S. Wong, K. L. Lee, W. W. Tang, Y. M. Fung, P. S. Chung, X. Wang, and S. Wan. Working with them really makes my research life much more pleasant and fruitful.

TABLE OF CONTENTS

WAVELENGTH SELECTION AND SWITCHING IN SHORT PULSES GENERATED FROM SEMICONDUCTOR LASERS

1 INTRODUCTION

In recent development of optical wavelength-division-multiplexed communication system, ultra-short optical pulse generation has been playing an important role. To fulfil the purpose of a multi-channel system, an optical source producing wavelength-tunable pulses with a high tuning speed is definitely useful. Therefore, the investigation of the transient dynamics of wavelength switching has attracted much attention.

This chapter reviews the development of wavelength-tunable ultra-short pulses generated from semiconductor lasers. *Section 1.1* gives a brief overview of ultra-short pulses generation in semiconductor lasers. *Section 1.2* presents different methods of wavelength selection and switching in ultra-short pulses generated from semiconductor lasers. *Section 1.3* describes the structure of this thesis.

1.1 Ultra-short Pulses Generation in Semiconductor Lasers

Ultra-short optical pulses can be generated from semiconductor lasers with a simple setup. Historically, the modulation of laser cavity loss, proposed by Hellwarth in 1961, was the first method for generating large bursts of radiation from a laser [1]. After tens of year's development, the gain-switching, Q-switching and mode locking schemes have become the common techniques to generate picosecond pulses with high repetition rates and peak power.

Gain-switching is known as one of the simplest techniques for generating picosecond optical pulses. It relies upon the switching of the optical gain through the modulation of a driving current. The idea originated from observations of relaxation oscillations when turning on a diode laser from below threshold using electrical pulses with a fast leading edge. It is noticed that the optical pulse width was considerably shorter than the electrical pulse. Gain switching consists of exciting the first spike of relaxation oscillation and terminating the electrical pulse before the onset of the next spikes. It means that the electrical pulse width should be rather short and should lie in the picosecond range. Alternatively, the modulation of a laser biased below threshold with a large sinusoidal signal also results in gain-switched optical pulses.

Q-switched lasers depend on the use of multi-section diodes together with a modulator or a saturable absorber in the laser cavity. These additional loss elements are used to switch the cavity loss on and off instantaneously. When the loss is switched on, lasing cannot occur due to the huge intracavity loss. As the loss is switched off, stimulated emission begins and develops into an intense pulse. Similar with the gain-switching scheme, frequency chirp is induced in the output pulses.

Mode-locking of semiconductor lasers can be achieved by applying current modulation or a saturable absorber. In time domain, the current modulation is considered as a switch that opens/closes the gate for the laser medium. Only the pulses that are just in the active medium when the gate is open are amplified by a short burst of stimulated emission. In frequency domain, the side bands should match with the original laser mode frequencies, and force then to have the same phase as the sidebands. Since all the sidebands are in phase, all the laser modes will have the same phase and mode-locking is achieved. In general, mode-locked pulses have the advantages of short pulse width, high peak power and low timing jitter. Usually, an external cavity is needed for actively mode-locking.

In contrast to mode locking and Q-switching techniques, gain switching has the advantage that no external cavity and no sophisticated fabrication technology are required. Also, the repetition rate of gain-switched pulses can be varied easily by changing the driving conditions. On the other hand, mode-locked pulses have the advantages of short pulse width and low timing jitter. Therefore, gain-switching and mode-locking become the popular techniques in ultra-short pulse generation.

1.2 Wavelength Selection and Switching in Short Pulses Generated from Semiconductor Lasers

As mentioned in *Section 1.1*, multi-wavelength short pulses can be readily generated by gain-switching, Q-switching or mode-locking a Fabry-Perot laser diode. However, it is very important for the pulses to be wavelength selectable in order to meet the multi-channel purpose. Therefore, the generation of single-wavelength and wavelength-tunable pulses becomes interesting research areas.

The simplest method to generate single-mode short pulses is gain-switching a distributed feedback (DFB) laser diode. However, the output wavelength can only be slowly tuned with temperature. A similar approach is direct modulation of a distributed Bragg reflector (DBR) laser. Wavelength tuning can be realized by injecting carrier into the reflector region, causing shifting of the reflection wavelength [2-5]. By this scheme fast tuning speed and a limited tuning range can be obtained, but complicated fabrication of the laser diode is required.

Without complicated fabrication process, wavelength-tunable pulses can also be generated from simple Fabry-Perot laser diodes. By external injection of light from a wavelength-tunable source, single-mode pulses can be produced with high side-mode suppression ratio and large tuning range [6]. Besides the injection seeding approach, by the self-seeding scheme wavelength-tunable pulses can also be generated with only one laser source [7,8]. Optical feedback to the laser diode is obtained by constructing an external cavity. In order to obtain single-mode oscillation, wavelength selective element such as a FP-resonator [9], a fiber grating [10] or a fiber with large dispersion [11] is added in the external cavity.

However, reviewing the different approaches of wavelength-tunable pulse generation the wavelength tuning speed is limited by the mechanical adjustment of the external cavity in most cases. In this thesis, fast switching of the output wavelength is demonstrated with various approaches without mechanical modification of the external cavity. Also, the switching speed is investigated for the first time. The details of the working principles and the measuring technique will be presented in *Chapter 2*.

1.3 Structure of the Thesis

The aim of this work is to investigate the dynamics of fast wavelength switching of short pulses generated from semiconductor lasers. Different configurations of semiconductor lasers are constructed and the switching transients are studied by the spectrally resolved analysis.

Chapter 1 gives a brief review of ultra-short pulse generation of semiconductor lasers. Also, various methods of generating wavelength-tunable pulse are reviewed.

Chapter 2 focuses on the principles of the configurations demonstrated in this thesis. The idea of the spectrally resolved analysis is also described.

Chapter 3 details the configuration of switching between single-mode and dual-mode operations of a self-seeded Fabry-Perot laser using a two-chromatic fiber grating. Fast switching between the two different operations is investigated.

Chapter 4 focuses on the mutual injection seeding scheme. Wavelength-tunable pulses are generated and the fast switching between different wavelengths is studied.

Chapter 5 shows the experimental details of the fast spectral improvement of a distributed feedback laser with weak external feedback. The factors affecting the improvement and the switching transients are studied.

Chapter 6 concludes the work presented in this thesis, where the possible future work is also included.

At the end of this thesis two appendixes are attached. Appendix A lists the international publications resulted from the thesis work, and appendix B is the list of figures.

Reference

1. R. W. Hellwarth, "Control of Fluorescent Pulsations", *Adcances in Quantum Electronics*, J. R. Singer, Ed., New York: Columbia university Press, 1961, pp. 334-341.

2. H. Kobrinski, M. P. Vecchi, T. E. Chapuran, J. B. Georges, C. E. Zah, C. Caneau, S. G. Menocal, P. S. Lin, A. S. Gozdz, and F. J. Favire, "Simultaneous fast wavelength switching and intensity modulation using a tunable DBR laser", *IEEE Photonics Technol. Lett.*, vol. 2, pp. 139-142, 1990.

3. F. Delorme, P. Gambini, M. Puleo, and S. Slemples, "Fast tunable 1.5 mm distributed Bragg reflector laser for optical switching applications", *Electron. Lett.*, vol. 29, pp. 41-43, 1993.

4. Y. Kotaki, M. Matsuda, M. Yano, H. Ishikawa, and H. Imai, "1.55 μm wavelength tunable FBH-DBR laser", *Electron. Lett.*, vol. 23, pp. 325-327, 1987.

5. S. Murata, I. Mito, and K. Kobayashi, "Tunable DBR laser with wide tuning range", *Electron. Lett.*, vol. 24, pp. 557-579, 1988.

6. Yasuhiro Matsui, Satoko Kutsusawa, Shin Arahira and Yoh Ogawa, "Generation of wavelength tunable gain-switched pulse from FP-MQW lasers with external injection seeding", *IEEE Photonics Technol. Lett.*, vol. 9, pp. 1087-1089, 1997.

7. M. Cavelier, N. Stelmakh, J. M. Xie, L. Chusseau, J.-M. Lourtioz, C. Kazmierski and N. Bouadma, "Picosecond (<2.5ps) wavelength-tunable (~20nm) semiconductor laser pulses with repetition rates up to 12 GHz," *Electron. Lett.*, vol. 28, pp. 224-226, 1992.

8. M. Schell, D. Huhse, A. G. Weber, G. Fischbeck, D. Bimberg, D. S. Tarasov, A. V. Gorbachov, and D. Z. Garbuzov, "20nm wavelength tunable single mode picosecond pulse generation at 1.3μm by a self-seeded gain-switched semiconductor laser", *Electron. Lett.*, vol. 28, pp. 2154-2155, 1992.

9. L. P. Barry, R. F. O'Dowd, J. Debau, and R. Boittin, "Tunable transform-limited pulse generation using self-injection locking of an FP laser", *IEEE Photonics Technol. Lett.*, vol. 5, pp. 1132-1134, 1993.

10. Hao Ding, Shenping Li, Zujie Fang and Kam Tai Chan, "Wavelength switching of semiconductor laser by self-seeded from a chirped fiber Bragg grating", *IEEE Photonics Technol. Lett.*, vol. 9, pp. 901-903, 1997.

11. D. Huhse, M. Schell, J. Kaessner, D. Bimberg, I. S. Trasov, A. V. Gorbachov, and D. Z. garbzov, "Generation of electrically wavelength tunable ($\Delta\lambda$=40nm) singlemode laser pulse from 1.3 μm Fabry-Perot laser by self-seeding in a fiber-optic configuration", *Electron. Lett.*, vol. 28, pp. 157-158, 1994.

2 PRINCIPLES AND THEORIES

This chapter puts the focus on the principles of the ideas in this thesis. In the following chapters, wavelength-tunable pulse generation is demonstrated by self-seeding or mutual injection seeding scheme. The switching transients of different operation modes are studied using the spectrally resolved analysis technique.

In this chapter, *Section 2.1* presents the principle of generating single-wavelength or dual-wavelength pulses from Fabry-Perot laser diode using the self-seeding technique. *Section 2.2* is devoted to the idea of synchronous injection seeding, together with the explanation of the compensated dispersion tuning of the output wavelength. *Section 2.3* includes the idea of spectral improvement of distributed feedback laser with external cavity providing optical feedback. Finally, *Section 2.4* gives the details of the principle of the spectrally resolved analysis in measuring the switching transient of lasers.

2.1 Principle of Wavelength Switching in Self-Seeded Lasers

The basic idea of self-seeding scheme is that a gain-switched Fabry-Perot laser diode (FP-LD) is coupled to an external cavity for monochromatic pulse generation and is then fed back to the laser diode [1, 2]. The requirement for self-seeding is that the weak and quasi-monochromatic feedback must arrive at the laser diode during the pulse buildup time. After several round-trip cycles, the stable single-mode oscillation can be obtained.

The mechanism of self-seeding is explained in Fig. 2.1. Wavelength-selective element such as a fiber grating has been used to separate the cavity modes of the FP-LD and then feed back during a narrow time window. Note that the required feedback is weak and quasi-monochromatic. The feedback signal must arrive during pulse build-up of the laser diode. Hence, the round-trip time in the external cavity

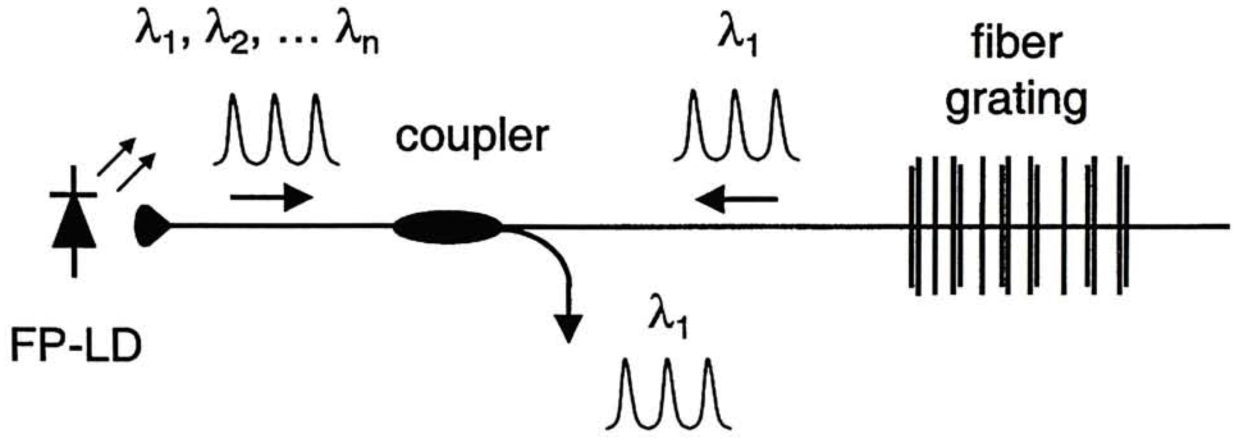

Fig. 2.1 *Schematic illustration of self-seeding approach in single-mode pulse generation. FP-LD: Fabry-Perot laser diode.*

must be close to, but slightly smaller than, a give multiple of the current modulation period. If coincidence occurs with the injection frequency of a given cavity mode during pulse build-up, the injection driven field will be amplified and will dominate the noise-driven fields corresponding to other modes. As a consequence, stable single-mode oscillation is generated and mode selection can be obtained.

As the first pulse is generated from the laser diode, it still shows multi-wavelength characteristic. When the first wavelength-selected pulse is fed back into the laser diode, the oscillation of the selected longitudinal mode is enhanced and other modes are suppressed. The spectral power of that selected mode continues to accumulate and finally a stable single-mode output is obtained. The dynamic change of the laser diode can be described by the following rate equations:

$$\frac{dN}{dt}=\frac{I}{q}-\frac{N}{\tau_s}-\sum_{i=-M}^{M}\Gamma\upsilon_g g_i S_i \qquad \text{(Eq. 2.1)}$$

$$\frac{dS_i}{dt}=\Gamma\upsilon_g g_i\left(1-\varepsilon\frac{\Gamma}{V}\sum S_i\right)S_i+\frac{\beta N}{\tau_s}-\frac{S_i}{\tau_p}+P_{fb,i(t)} \qquad \text{(Eq. 2.2)}$$

Table 2.1 lists the used parameters in Eq. 2.1 and 2.2. The optical input term $P_{fb,i(t)}$ in Eq. 2.2 is zero for all modes except for the selected mode k. Here $P_{fb,k} = r \cdot 0.5 \cdot \alpha_m \cdot \upsilon_g \cdot S_{n-1,k(t)}$ with $0.5 \cdot \alpha_m \cdot \upsilon_g \cdot S_{n-1,k(t)}$ the emitted power in the k^{th} mode of the laser pulse and r the feedback efficiency. A parabolic gain profile is assumed to be as Eq. 2.3

$$g_i = \left[\frac{A_{o,i}(N - N_o)}{V} - \frac{(\lambda_i - \lambda_o)^2}{G_o^2} \right] \qquad \text{(Eq. 2.3)}$$

where $A_{o,i} = A_o\ [\ 1 - 0.013\ (\lambda_i - \lambda_{offset})]$ is used to account for the increase in the different gain on the short wavelength side of the gain spectrum. The simulation results show that steady single-mode pulses can be obtained after four round-trip propagation cycles [3].

Symbol	***Physical Quantity***
N	Carrier number
S_i	Photon number of mode i
g_i	Gain of mode i
I	Applied current
q	Electron charge
τ_s	Carrier lifetime
$2M+1$	Total number of modes
Γ	Mode confinement factor
υ_g	Group velocity
ε	Gain compression parameter
V	Active layer volume
β	Spontaneous emission factor
τ_p	Photon lifetime
$A_{0,i}$	Differential gain of mode I
N_o	Carrier number for transparency
λ_o	Peak wavelength
G_o	Modal gain factor
α_m	Mirror loss

Table 3.1 *List of the parameters used in Eq. 2.1, 2.2 and 2.3*

Besides monochromatic feedback, it is noticed that dual-wavelength output can be generated by dual-wavelength feedback. To realize this scheme a two-chromatic fiber grating is used instead. It is also noticed that by controlling the carrier induced frequency chirp of the laser diode, the spectral overlap between the Fabry-Perot modes and the grating reflection band can be adjusted to select the emission wavelengths. Thus, by modulating the amplitude of the RF applied to the laser diode, fast switching between single-mode and dual-mode operations is realized. The experimental details of this scheme will be discussed in Chapter 3.

2.2 Principle of Synchronous Injection Seeding of two Lasers

The main idea of this scheme [4] relies on the dispersion of optical fibers. The schematic illustration of the synchronous injection seeding is shown in Fig. 2.2. The setup is composed of two Fabry-Perot laser diodes, two pieces of fibers and two optical circulators. FP-LD1 is gain-switched by RF signal of sinusoidal form. Owing to the group velocity dispersion provided by the piece of single-mode fiber, the wavelength components in the pulses emitted from FP-LD1 are temporally separated and then inject into the FP-LD2. FP-LD2 is driven with the same RF frequency as the one that drives FP-LD1. The time delay between the two RF signals however can be accurately controlled. Since different wavelength components arrive FP-2 at different time instant, the one arrives FP-2 during its pulse build up time can be successfully injection-seeded and set FP-2 into single-mode oscillation. To generate wavelength tunable pulse from the two gain-switched FP laser diodes, one can adjust the time delay such that the desired wavelength can be selected.

To make the total cavity dispersion to be zero such that different wavelength component has same cavity round trip propagation time, a fiber with opposite dispersion is integrated into other part of the cavity. Therefore, the wavelength tuning can be performed simply by adjusting the time delay between the two RF signals.

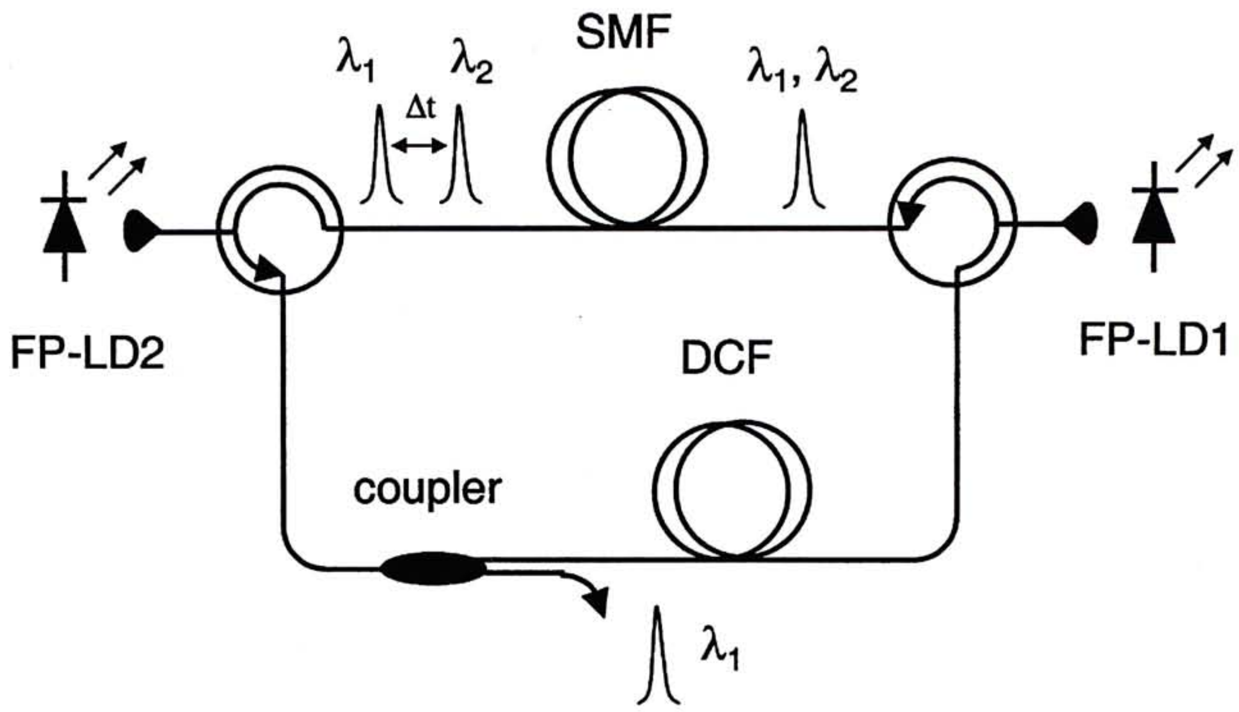

Fig. 2.2 *Schematic illustration of wavelength-tunable pulse generation by the mutual injection seeding approach. FP-LD1, FP-LD2: Fabry-Perot laser diodes; SMF: single-mode fiber; DCF: dispersion compensated fiber.*

In Chapter 4, this scheme is experimentally demonstrated and a wavelength tunable output is obtained. The transient dynamics of the wavelength selection and switching are also investigated.

2.3 Principle of Fast Spectral Improvement in DFB laser with Optical Feedback

As described in *Section 2.1*, wavelength selection can be achieved by self-seeding of a gain-switched Fabry-Perot laser diode. Besides, it is noticed that when similar scheme is applied to a distributed feedback laser diode, spectral improvement of the output is obtained [5]. In the gain switching process, the large fluctuation of the carrier density causes excitation of the other side modes and frequency chirp is also introduced in the laser output. These problems will lead to a degradation of the side-mode suppression ratio (SMSR) and result in spectral width broadening of the output pulses. However, with small amount of optical feedback, the large degradation is found to be greatly reduced by reinforcing the oscillation of the main mode.

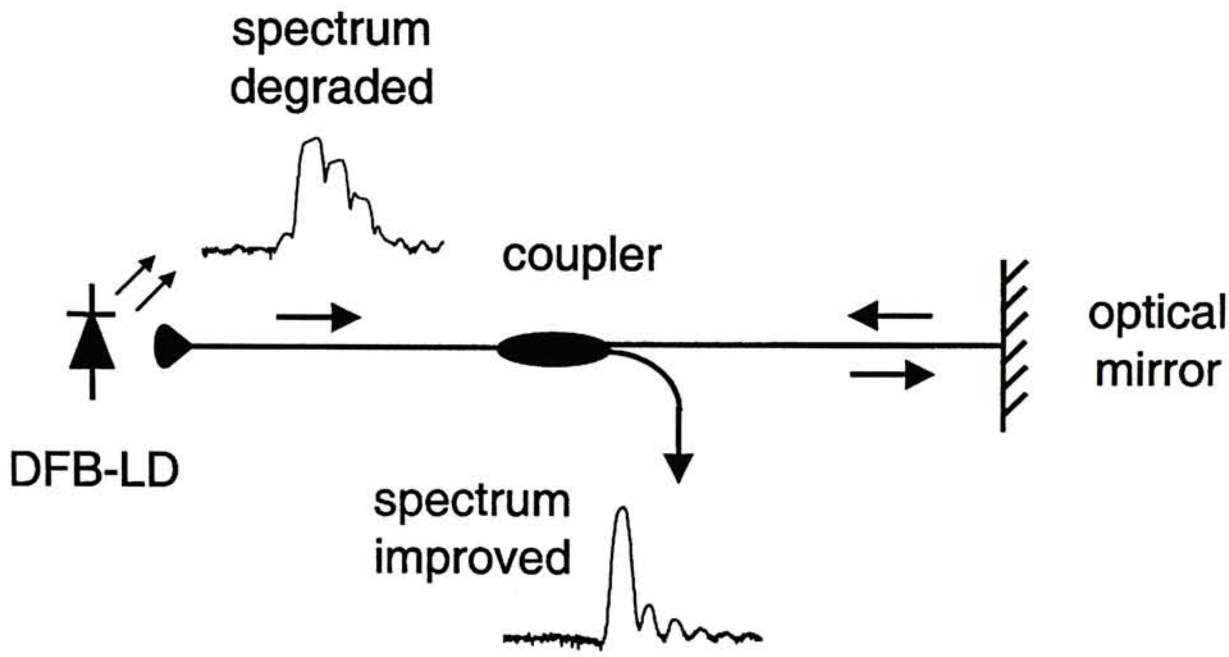

Fig. 2.3 *Schematic illustration of spectral improvement of a distributed feedback laser with external feedback. DFB-LD: distributed feedback laser diode.*

Fig. 2.3 shows the schematic illustration of the spectral improvement scheme. In contrast to the self-seeding scheme, an optical mirror is used here to provide optical reflection. With suitable adjustment of the pulse arrival time, the oscillation of the main mode will be reinforced and both the SMSR and the spectral width are improved. The detailed investigation is presented in *Chapter 5*.

2.4 Principle of Spectrally Resolved Analysis

In this thesis, the transient dynamics of the laser diodes are studied by the spectrally resolved analysis. This technique puts the focus on the investigation of the evolution of the spectral characteristics of laser. Fig. 2.4 shows the working principle. Using the self-seeding scheme as example, the Fabry-Perot laser diode changes from multi-mode to single-mode oscillation as it is self-seeded by the single-mode feedback pulses. To study the switching transients one should make the switching process occur periodically. Therefore, the square-wave generator is used here to turn on and off the frequency synthesizer at a low frequency. Since there is a trigger between the square-wave generator and the boxcar integrator, the boxcar integrator can accurately gate the pulses from each round-trip cycle. It is also important to know the pulse propagation time t for one round trip, which depends on the length of the external cavity:

$$t = \frac{2nL}{c} \tag{2.4}$$

where n is the refractive index of the fiber in the external cavity, c the speed of light and L the external cavity length. The gate width of the boxcar integrator is set to just shorter than t to ensure that the gated pulses are come from one single round trip. The output spectrum of the laser diode during that round-trip cycle can be obtained by sweeping the electrical tunable filter. After the result is recorded, one can investigate the next round trip by increasing the time delay of the gate by t. The process repeats

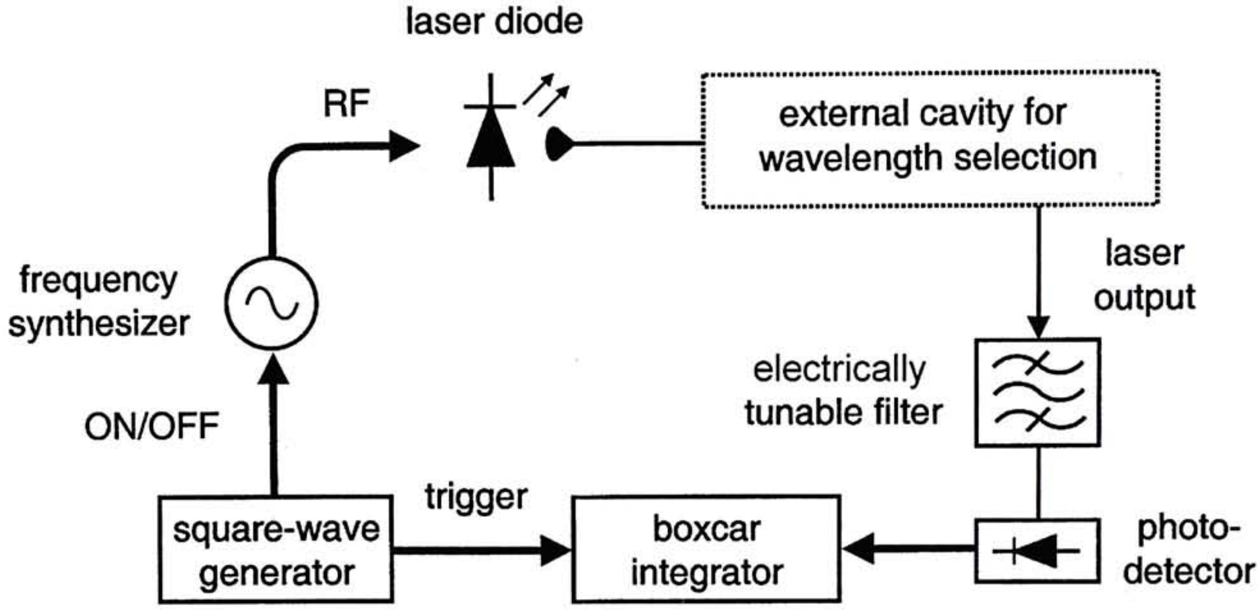

Fig. 2.4 *Schematic illustration of the spectrally resolved analysis for measuring transient dynamics of semiconductor laser.*

in the following round-trip cycles until a stable output is observed. At this stage the evolution of output spectrum is achieved. This technique is found to be useful in measuring the switching dynamics of laser diodes in different configurations. In the rest of this section a simple experiment is demonstrated to give detailed explanations of the spectrally resolved analysis.

Fig. 2.5 shows the experimental setup for the investigation of the dynamics of single-mode formation in a self-seeded Fabry-Perot laser diode (FP-LD). The wavelength-selective element is a piece of fiber Bragg grating connected in the external cavity. Since the external cavity length L is about 100 m, by Eq. 2.4 the pulse round-trip propagation time t can be estimated as 1 μs. The FP-LD is gain-switched by an RF signal at 1 GHz and the frequency synthesizer is switching on and off by the square-wave generator. The RF signal applied to the laser diode is shown in Fig. 2.6. The

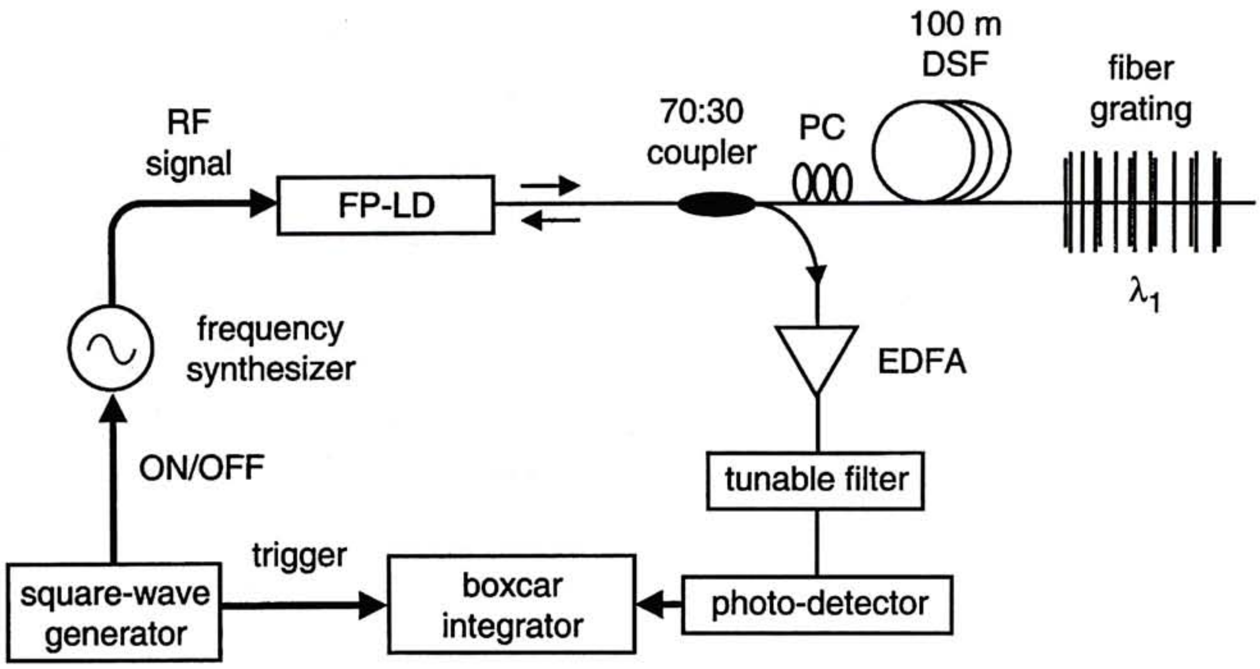

Fig. 2.5 *Setup on the measurement of the dynamic behavior of single-mode pulse formation in a self-seeded Fabry-Perot laser diode. FP-LD: Fabry-Perot laser diode; PC: polarization controller; DSF: dispersion shifted fiber; EDFA: erbium-doped fiber amplifier.*

waveform is a 1 GHz sinusoidal wave turning on and off at 10 kHz. Note that the waveform is captured from a 500 MHz oscilloscope which is triggered directly by the square wave. The 1 GHz signal cannot be triggered and the aliasing effect of sampling thus results in a faulty signal frequency. When the RF signal is turned on, the output from the self-seeded FP-LD will remain at multi-mode in the subsequent 1 μs duration (0^{th} round trip). In the next 1 μs (1st round trip), the laser diode is seeded by reflected pulses and begins to develop a sigle-mode characteristic. The process repeats in the following few round-trip cycles until a stable dual-wavelength output is obtained. After 50 round-trip cycles (50 μs), the RF signal is switched off for the next 50 μs. Then the same mechanism occurs again and the transient dynamics of the laser diode can be measured.

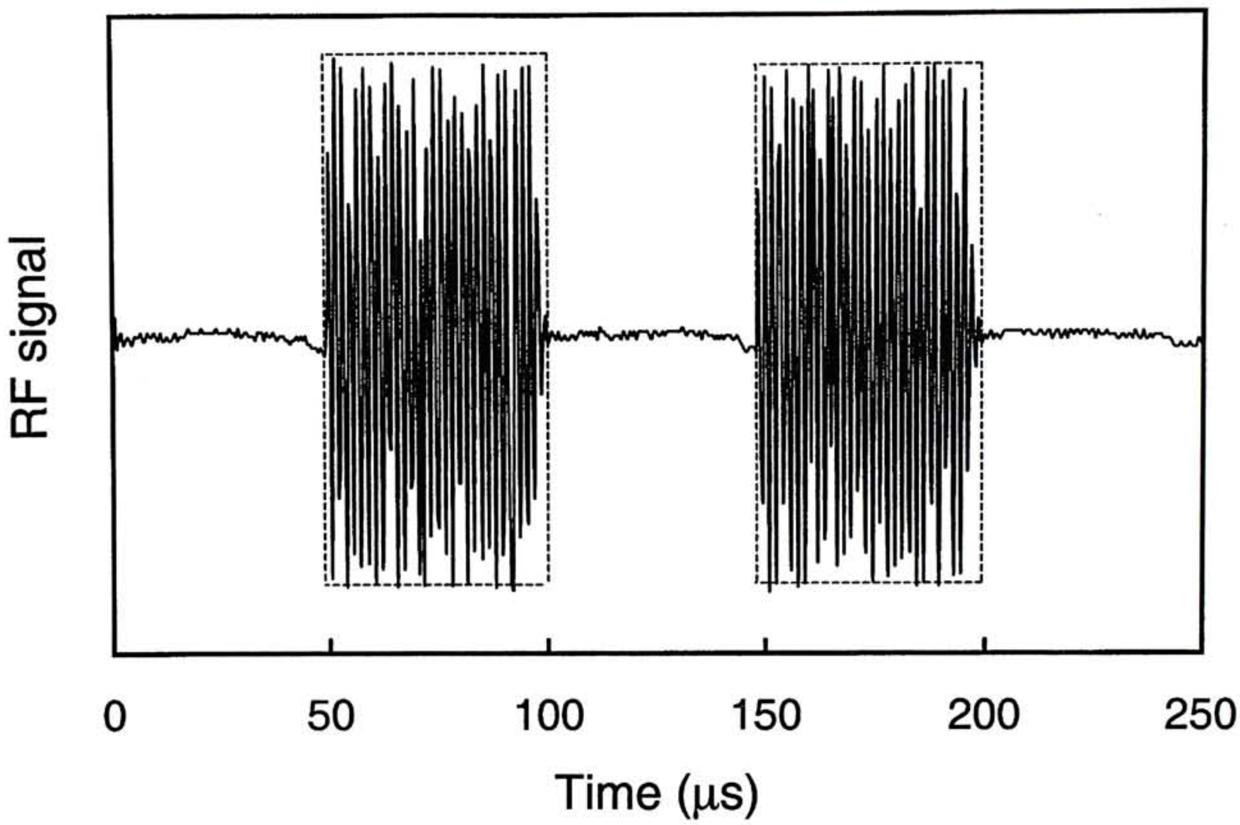

Fig. 2.6 *The modulated RF signal waveform applied to the laser diode for switching dynamics investigation.*

For the pulse round-trip propagation time is 1 μs, the gate width of the boxcar integrator is set to 0.9 μs to ensure that the gated pulses are from the same round trip. By tuning the gate to a specific round trip, one can obtain the laser spectrum during that particular round-trip cycle by sweeping the tunable filter. The laser spectrum of the next round-trip cycle can be obtained simply by increasing the time delay of the gate by 1 μs. Thus the boxcar integrator will gate the pulses only from the next round-trip cycle. Similar procedures are repeated in the following round-trip cycles and finally the spectral evolution is achieved. Fig. 2.7 shows the output spectra in the first few round trips as the RF signal switches on. The result shows the gradual buildup of single-mode characteristic with increasing round trip cycle number. The

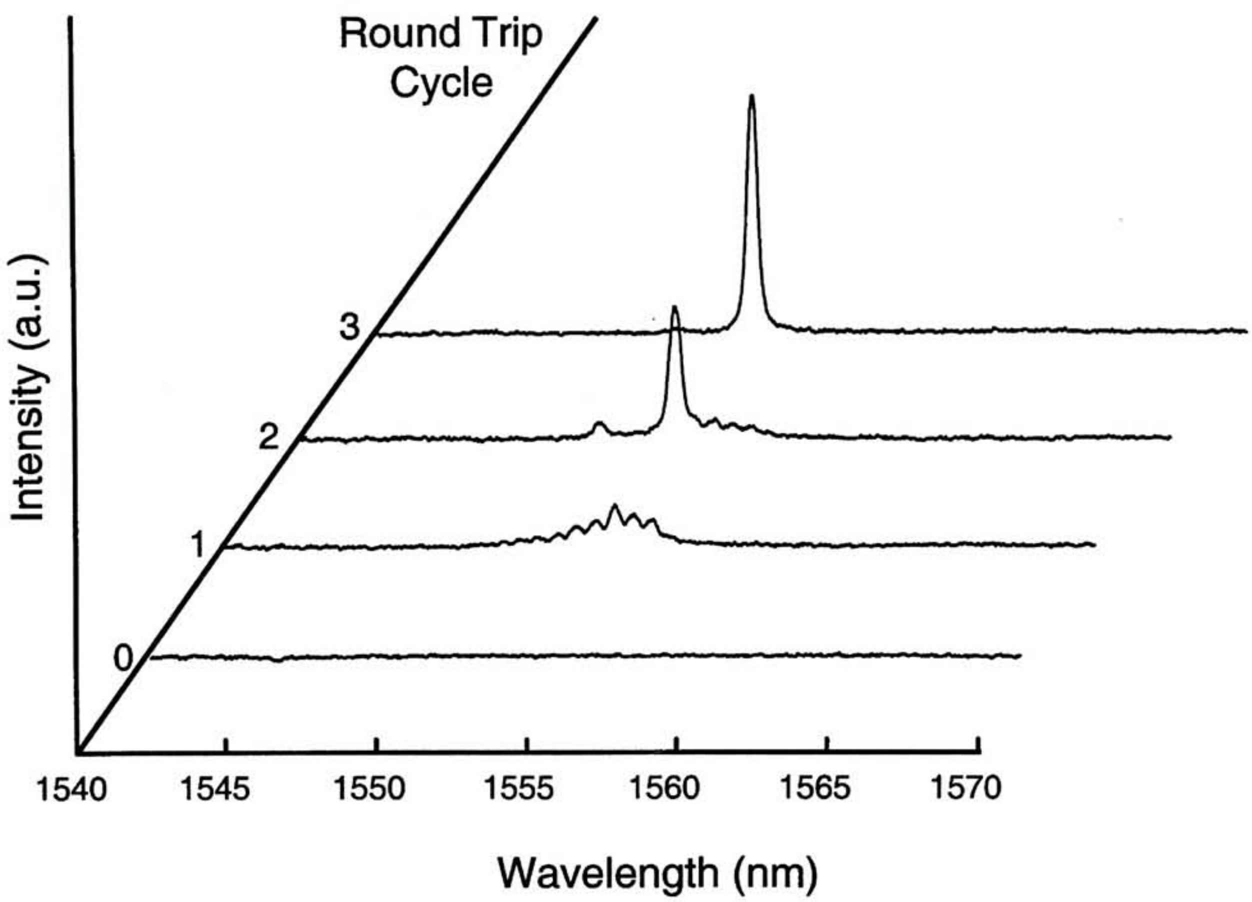

Fig. 2.7 *Evolution of the output spectrum in the first few round-trip cycles of single-mode formation.*

output is found to be stabilized within four round-trip cycles, which is consistent with the results from another group [3].

The spectrally resolved analysis is found to be useful in different configurations. In the following chapters, this technique is used to investigate the transient dynamics of wavelength selection and switching in semiconductor lasers.

Reference

1. M. Cavelier, N. Stelmakh, J. M. Xie, L. Chusseau, J.-M. Lourtioz, C. Kazmierski and N. Bouadma, "Picosecond (<2.5ps) wavelength-tunable (~20nm) semiconductor laser pulses with repetition rates up to 12 GHz," *Electron. Lett.*, vol. 28, pp. 224-226, 1992.

2. M. Schell, D. Huhse, A. G. Weber, G. Fischbeck, D. Bimberg, D. S. Tarasov, A. V. Gorbachov, and D. Z. Garbuzov, "20nm wavelength tunable single mode picosecond pulse generation at 1.3μm by a self-seeded gain-switched semiconductor laser", *Electron. Lett.*, vol. 28, pp. 2154-2155, 1992.

3. D. Huhse, M. Schell, W. Utz, J. Kaessner, and D. Bimberg, "Dynamics of single-mode formation in self-seeded Fabry-Perot laser diodes", *IEEE Photonics Technol. Lett.*, vol. 7, pp. 351-353, 1995.

4. K. Chan and C. Shu, "Electrically wavelength-tunable pulses generated by synchronous two-way injection seeding", *IEEE Photonics Technol. Lett.*, vol. 11, pp. 170-172, 1999.

5. L. P. Barry, J. Debeau, and R. Boittin, "Simple technique to improve the spectral quality of gain-switched pulses from a DFB laser", *Electron. Lett.*, vol. 30, pp. 2143-2145, 1994.

3 SWITCHING DYNAMICS BETWEEN SINGLE-MODE AND DUAL-MODE PULSE EMISSIONS FROM A SELF-SEEDED LASER DIODE

Basing on the principle described in *Section 2.1* of Chapter 2, self-seeded dual-wavelength pulses are generated from a Fabry-Perot laser diode in an external cavity containing a two-chromatic fiber grating. Electrical switching between single-mode and dual-mode operations is demonstrated by controlling the amplitude of the RF signal applied to the laser diode. The principle is based on carrier induced frequency chirp that determines the spectral overlap of the Fabry–Perot modes with the grating reflection band during the pulse buildup time. Using the spectrally resolved analysis described in *Section 2.4* of Chapter 2, the switching dynamics is investigated and the results show that the steady states can be reached after about five to six round-trip cycles. The buildup of single-mode emissions is slightly faster than that of the dual mode.

In this chapter, *Section 3.1* contains a brief introduction of this experiment. The experimetal details are included in *Section 3.2* with experimental results and discussion. Finally a summary of the experiment is given in *Section 3.3*.

3.1 Introduction

Wavelength-tunable single-mode short pulses are readily generated from a self-seeded Fabry-Perot laser diode (FP-LD) [1]. Much research has been focused on the dynamics of single-mode formation in this scheme. The switching from a multi-mode to a single-mode wavelength [2], from a single-mode to another competing single-mode wavelength [3, 4], and from a continuous wave (CW) injection-seeded wavelength to a pulsed self-seeded wavelength [5] have been investigated. It was discovered that a stable operation could be achieved within five to ten round-trip propagation cycles in the external cavity. The switching speed compares favorably with the hundreds of round trips generally needed for stabilization in the mode-locking approach [6].

Recent advances in multi-channel wavelength-division-multiplexing systems reveal the importance of dual-wavelength picosecond pulse sources. Different approaches of self-seeding have been explored to generate dual or multi-wavelength pulses using multiple fiber gratings [3, 7], multiple-path external cavity [8, 9], or time-domain filtering in a dispersive cavity [10]. In this chapter, an effective approach for electrical switching between single-mode and dual-mode operations is developed. A two-chromatic fiber grating is used for wavelength selection in a self-seeded FP-LD. By controlling the carrier induced frequency chirp, the spectral overlap between the Fabry–Perot modes and the grating reflection band can be adjusted to select the emission wavelengths. The dynamics of switching is also studied using a boxcar integrator. It has been found that about five to six round trips are required to stabilize the outputs. The result indicates that fast switching in the order of nanoseconds is possible using a fiber cavity of a few centimeters.

3.2 Experimental Details and Discussion

Fig. 3.1 shows the experimental setup. The laser source is a 1.55 μm FP-LD with a 1.52 nm mode spacing and a 37.8 mA CW threshold current. The laser diode is biased below threshold and is gain-switched with an electrically amplified sinusoidal signal at 1.006 GHz. A square-wave generator is connected to the radio frequency (RF) synthesizer and can be used to modulate the signal amplitude. The all-fiber external cavity contains a 70/30 coupler, a polarization controller (PC), a 100 m long dispersion shifted fiber (DSF), and a 1 cm long two-chromatic fiber grating. The grating is manufactured by double exposures of a hydrogen-loaded fiber by ultraviolet light. Two different Bragg periods are formed at about the same location

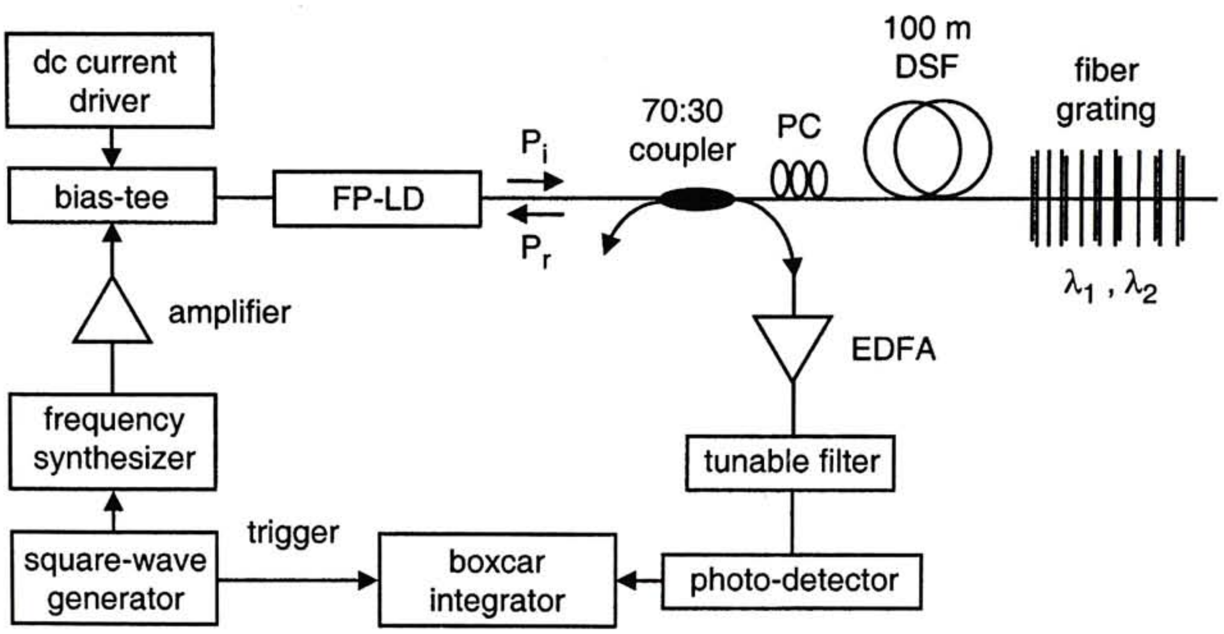

Fig. 3.1 *Measurement setup on the switching dynamics between single-mode and dual-mode operations of a self-seeded laser diode. FP-LD: Fabry-Perot laser diode; PC: polarization controller; DSF: dispersion shifted fiber; EDFA: erbium-doped amplifier.*

using two phase masks. The PC is used here to balance the effective feedback at the two wavelengths and to improve the spectral purity by suppressing the unselected FP modes. A stronger overlap of the polarizations of the selected feedback modes and the transverse electric modes in the laser diode will enhance the lasing and thus deplete the electrical carriers. Hence, the amplified spontaneous emissions of the other modes will become weaker. The 30% laser output is connected to an erbium-doped fiber amplifier (EDFA) for power enhancement. The amplified light then passes through an electrically tunable FP filter, which is used as a monochromator in measuring the evolution of different wavelength components. The light pulses are detected by a 32 GHz photodetector connected to a boxcar integrator.

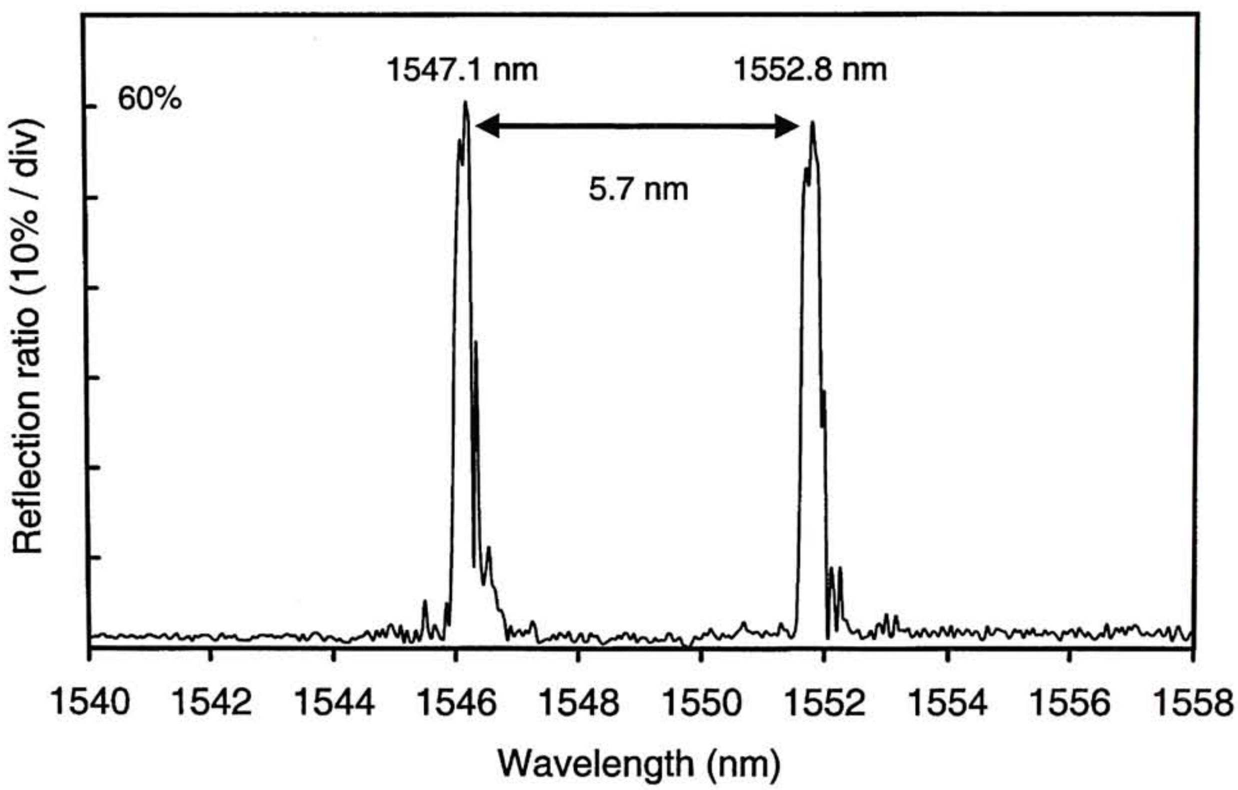

Fig. 3.2 *The reflection characteristics of the two-chromatic fiber grating.*

To achieve a dual-wavelength output, the reflection wavelengths of the fiber grating should overlap with two distinct longitudinal modes of the FP-LD. Fig. 3.2 shows the reflection characteristics of the fiber grating. The spacing of the reflection peaks in the fiber grating is 5.70 nm with a band-width of about 0.3 nm for each mode. Using the strain-tuning method [11], the two peaks can be precisely controlled for optimal overlap with the longitudinal modes of the laser diode.

Figure 3.3 shows the dependence of the output side-mode-suppression ratio (SMSR) on the RF signal applied to the FP-LD. At a high RF level (+25 to +26 dBm), effective dual-wavelength operation at λ_1=1545.7 nm and λ_2=1545.8 nm can be obtained. The SMSR is about 20 dB. As the RF level is reduced, the SMSR at λ_1 increases gradually while that at λ_2 decreases rapidly. Between +21 and +22 dBm, the output essentially becomes single mode and the laser emits only at λ_1. The result indicates that electrical switching between single-mode and dual-mode oscillations is possible when the RF amplitude is alternated between +21 and +25 dBm. This observation is explained by the frequency chirp of the FP-LD as a result of carrier-induced refractive index changes during pulse build-up. In another experiment without optical feedback, it is found that a 1 nm spectral broadening towards the short wavelength side of each mode when the RF amplitude is increased from +21 to +25 dBm. Since the 5.70 nm spacing between the reflection peaks of the fiber grating is slightly smaller than that between two distinct FP modes (6.08 nm) of the laser diode, simultaneous two-mode oscillation cannot be obtained without sufficient chirp. Self-seeding at λ_2 depends on spectral broadening in the blue side of the

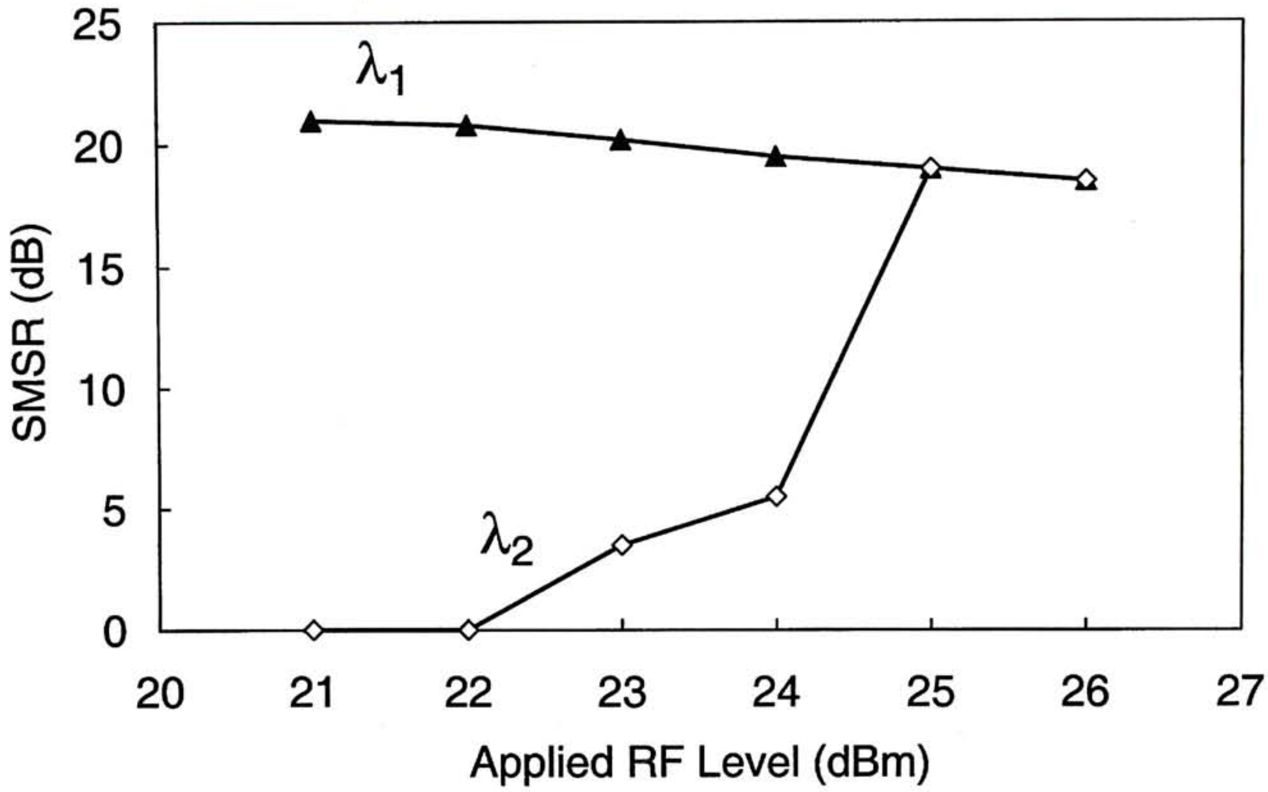

Fig. 3.3 *Dependence of the output SMSR on the applied RF signal level for pulse generation. $\lambda 1$=1545.7 nm and $\lambda 2$=1551.8 nm.*

corresponding longitudinal mode, which occurs only at a high RF signal level. However, since the grating reflection wavelength overlaps well with the mode at λ_1, a large SMSR is maintained over the range of the RF amplitude shown in Fig. 3.3.

The steady-state self-seeded outputs at single- and dual-wavelength operations are first studied using an optical spectrum analyzer of 0.1 nm resolution and a 32 GHz photodetector together with a digital sampling oscilloscope (not shown in Fig. 3.1). The external cavity length is about 100 m corresponding to a round-trip propagation time of 1 μs. In the experiment, the FP-LD is driven at 1.006 GHz. The feed-back ratio P_r / P_i (see Fig. 3.1) is measured to be about 6% in both single-wavelength and dual-wavelength operations. Figure 3.4(a) shows the dual-mode spectrum and the

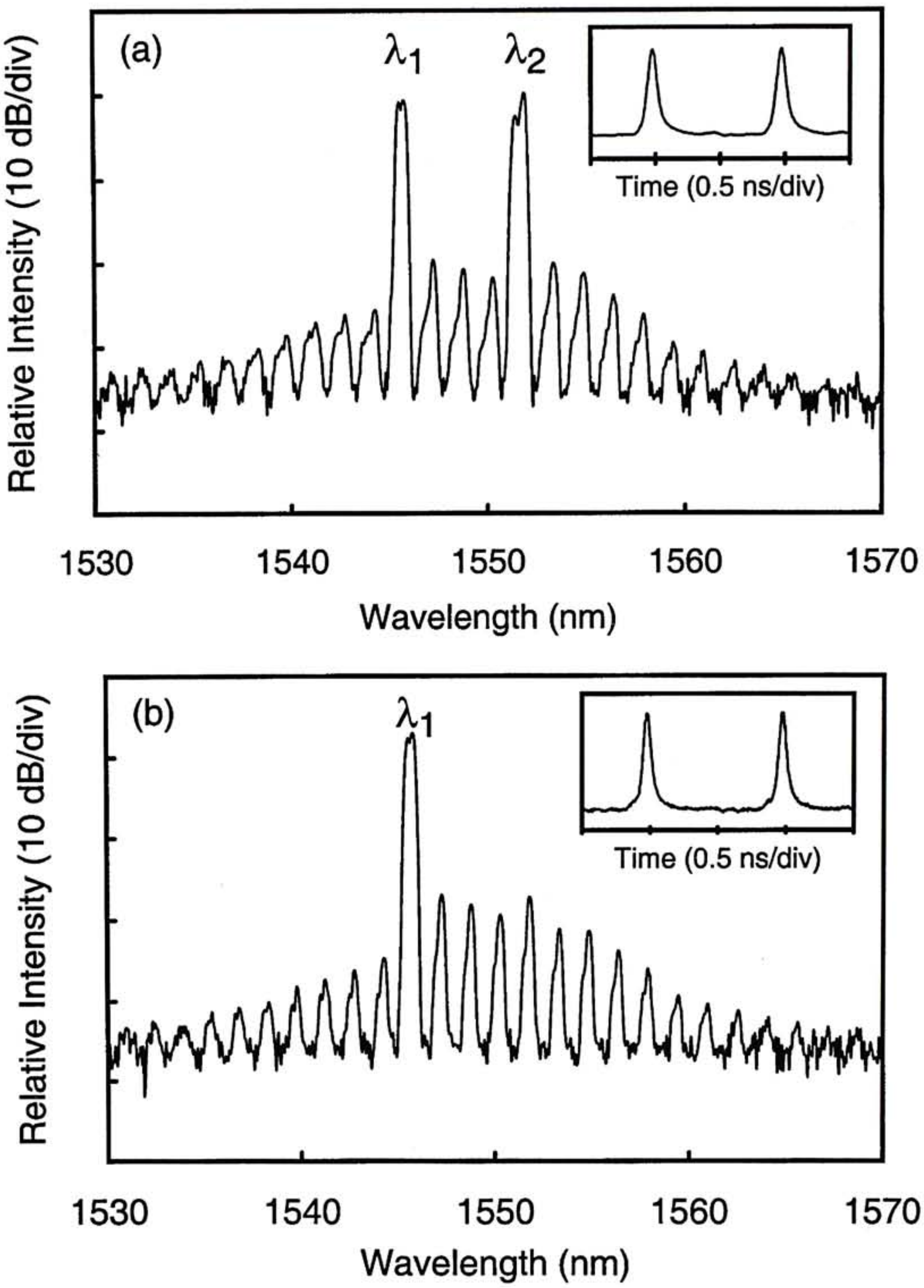

Fig. 3.4 *Output spectra and the corresponding pulses under (a) dual-mode operation and (b) single-mode operation.*

corresponding light pulses at +25 dBm applied RF signal. The peak wavelengths are located at 1545.7 nm (λ_1) and 1551.8 nm (λ_2) with a pulse width of 89 ps and a peak power of 1.39 mW. The two wavelengths have equal intensities with a SMSR of about 20 dB. The measured spectral widths for λ_1 and λ_2 are 0.52 and 0.63, respectively. Figure 3.4(b) shows the spectral and temporal outputs at +21 dBm applied RF signal. The single-mode wavelength is located at 1545.7 nm and the SMSR is slightly over 20 dB. The pulse width and the peak power are measured to be 68 ps and 1.07 mW, respectively.

To switch between single- and dual-wavelength outputs, one can simply vary the applied RF signal between +21 and +25 dBm. Fig. 3.5 shows the RF signal used in our experiment. The modulated waveform contains a 1.006 GHz sinusoidal signal with a periodic square-wave envelope at 10 kHz. The waveform is captured from a 500 MHz oscilloscope which is triggered directly by the square wave. The 1 GHz signal cannot be triggered and the aliasing effect of sampling thus results in a faulty signal frequency which happens to be about 200 kHz. Note that the operating frequency for single-mode and dual-mode oscillations remains unchanged during the switching process. Since the rise time and the fall time of the square wave generator are less than 10 ns, the transient will not affect the result significantly. The 100 m DSF is inserted to increase the round-trip propagation time of the optical pulses in the feedback loop to 1 μs. Hence, the gate width of the boxcar integrator can be set to 0.9 μs to ensure that the gated signal contains only pulses in the same round-trip cycle.

When the RF amplitude is changed from +21 to +25 dBm, the output from the self-seeded FP-LD will remain at single-mode in the subsequent 1 μs duration (0^{th} round trip). In the next 1 μs (1st round trip), the laser diode is seeded by reflected pulses

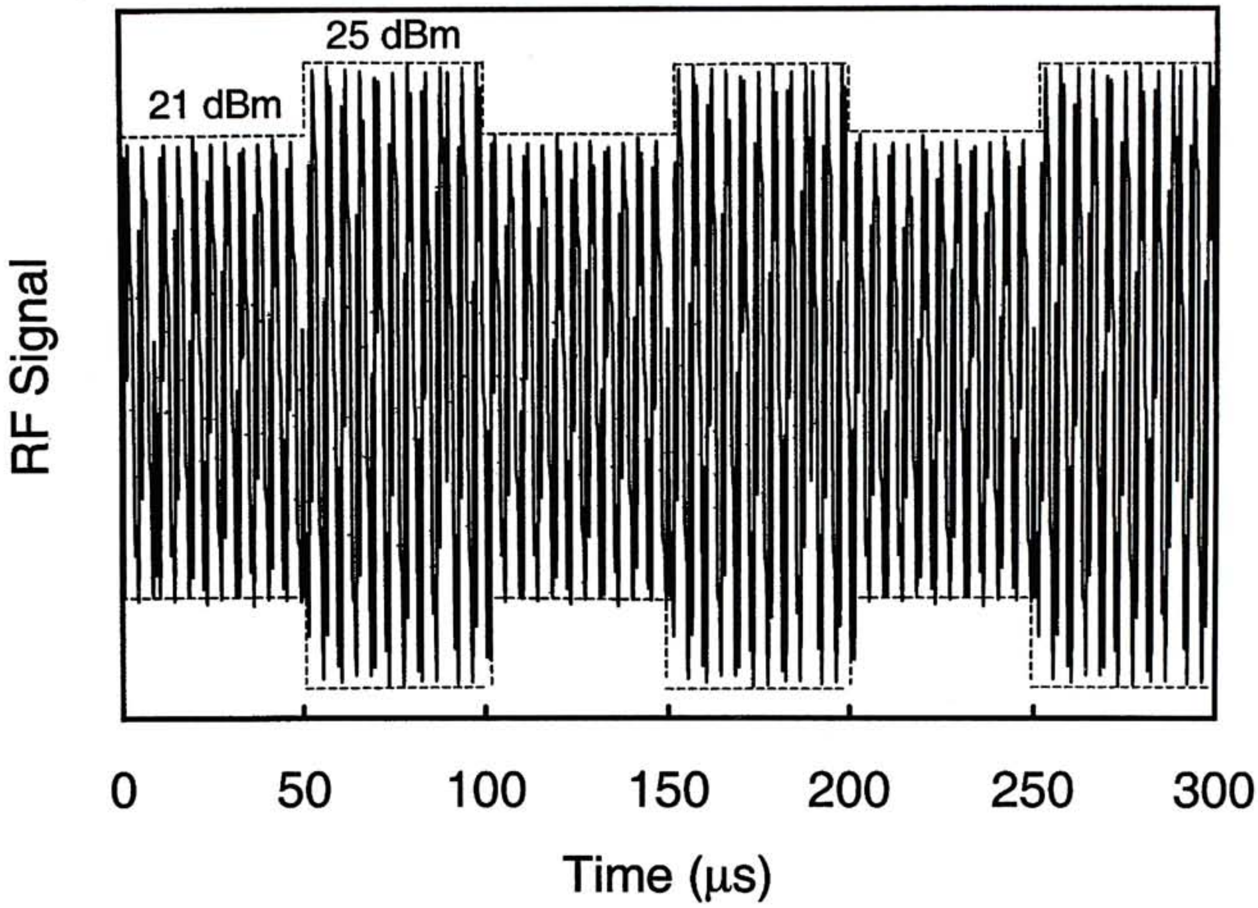

Fig. 3.5 *The modulated RF signal waveform applied to the laser diode for switching between single-mode and dual-mode operations.*

that begin to develop a dual-mode characteristic. Thus, the spectral power of the λ_2 mode starts to grow and the gain is shared between the two wavelengths. The process repeats in the following few round-trip cycles until a stable dual-wavelength output is obtained. After 50 round-trip cycles, the RF amplitude is switched back to +21 dBm. The reverse mechanism occurs and the laser diode is eventually turned back into single-mode operation.

Figure 3.6 shows the output spectra in the first few round trips when the laser diode is switched from single-mode to dual-mode operation. The result shows the gradual buildup of dual-mode characteristic with increasing round trip cycle number. A

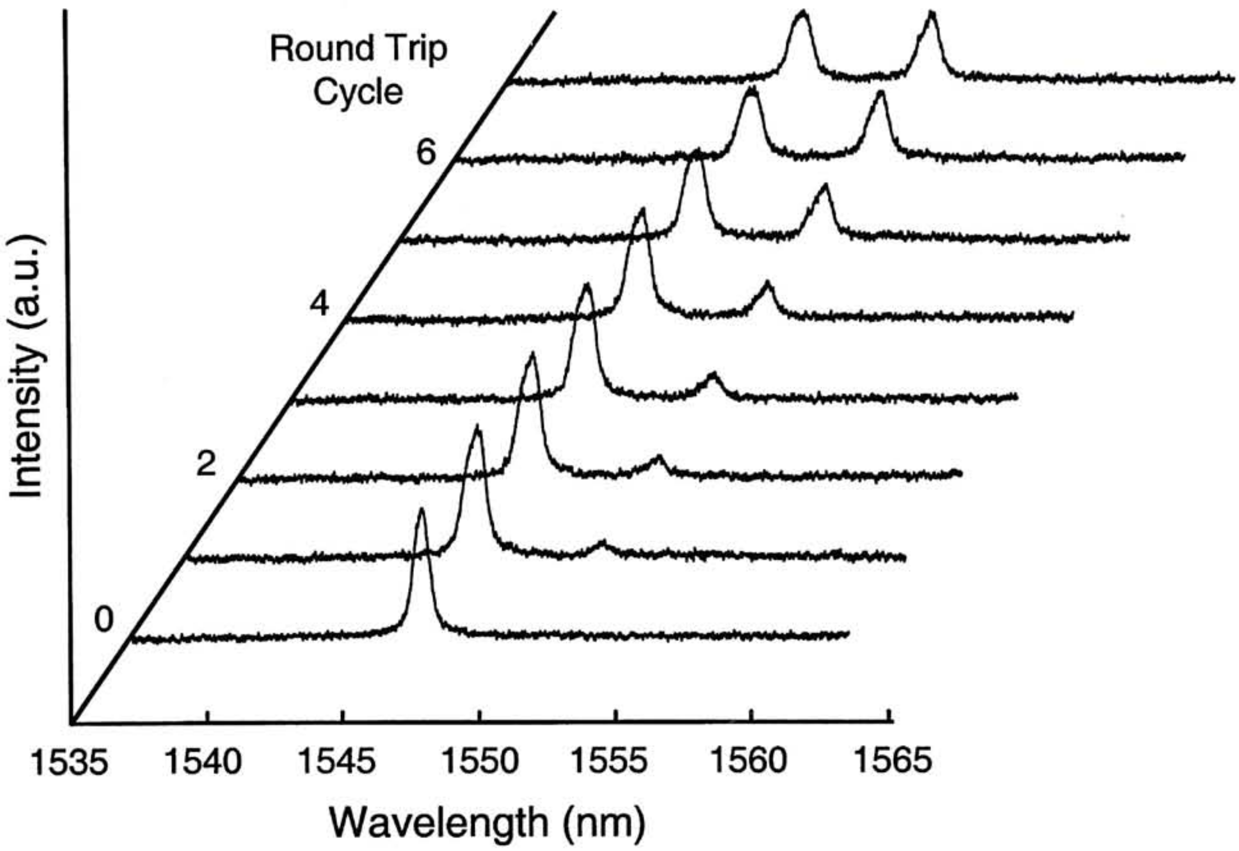

Fig. 3.6 *Output spectra showing the evolution from a single-mode to a dual-mode opeartion.*

stable output is observed after six round trips. Since the bandwidth of the tunable filter is 0.65 nm, the spectral resolution in the plots is lower than that in Fig. 3.4. The evolution of the spectrum from dual-mode to single-mode operation is shown in Fig. 3.7. The result shows that stable emission is attained in only five round trips and is slightly faster than that in the dual-mode formation. The observation is attributed to the sharing of the feedback power by two different wavelengths in the process of dual-mode formation. Since the effective feedback ratio of each mode becomes 3% instead of the 6% used in single-mode formation, the growth of the spectral power in each mode is slower. Our result is consistent with a separate report that the spectral evolution of a self-seeded FP-LD is faster near the gain peak region, where a larger feedback power is expected [3].

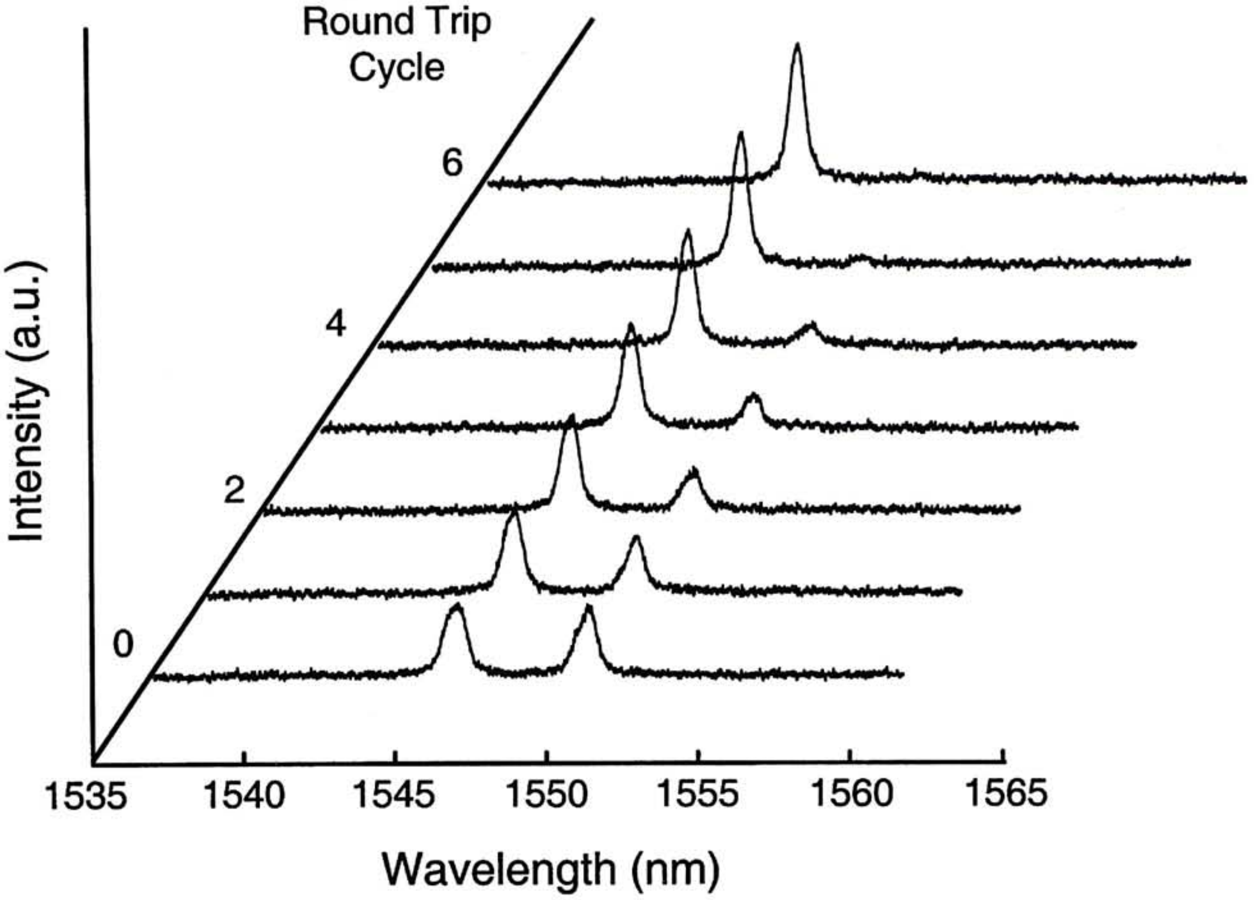

Fig. 3.7 *Output spectra showing the evolution from a dual-mode to a single-mode operation.*

3.3 Summary

In summary, fast switching between single- and dual-wavelength operations of a self-seeded FP laser diode is demonstrated in a fiber-optic external cavity at a constant operating frequency. The side-mode-suppression-ratio is maintained at about 20 dB in both cases. The time required to achieve stable operation is experimentally determined to be about five to six round trips. The result shows that fast switching in the order of nanoseconds is possible using a fiber cavity of a few centimeters.

Reference

1. M. Cavelier, N. Stelmakh, J. M. Xie, L. Chusseau, J.-M. Lourtioz, C. Kazmierski and N. Bouadma, "Picosecond (<2.5ps) wavelength-tunable (~20nm) semiconductor laser pulses with repetition rates up to 12 GHz," *Electron. Lett.*, vol. 28, pp. 224-226, 1992.

2. D. Huhse, M. Schell, W. Utz, J. Kaessner, and D. Bimberg, "Dynamics of single-mode formation in self-seeded Fabry-Perot laser diodes", *IEEE Photonics Technol. Lett.*, vol. 7, pp. 351-353, 1995.

3. D. Huhse, M. Schell, W. Utz, and D. Bimberg, J. A. R. Williams, L. Zhang, and I. Bennion, "Fast wavelength switching of semiconductor laser pulses by self-seeding", *Appl. Phys. Lett.*, vol. 69, pp. 2018-2020, 1996.

4. D. Huhse and D. Bimberg, "Competing mode suppression ratio of electrically wavelength tunable self-seeded lasers," *IEEE Photonics Technol. Lett.*, vol. 11, pp.167-169, 1999.

5. S. P. Yam and C. Shu, "All-optical wavelength switching in a semiconductor laser using self-seeding and external injection-seeding", *Appl. Phys. Lett.*, vol. 72, pp. 1024-1026, 1998.

6. P. A. Morton, R. J. Helkey, J. E. Bowers, "Dynamic detuning in actively mode-locked semiconductor lasers", *IEEE J. Quantum Electron.*, vol. 25, pp. 2621-2633, 1989.

7. L. P. Barry, J. M. Dudley, B. C. Thomsen, and J. D. Harvey, " Frequency-resolved optical gating measurement of 1.4 THz beat frequencies from dual wavelength self-seeded gain-switched laser diode", *Electron. Lett.*, vol. 34, pp. 988-990, 1998.

8. D. N. Wang and C. Shu, "Multiple optical paths in a self-seeding scheme for multiwavelength short pulse generation", *Appl. Phys. Lett.*, vol. 71, pp. 1305-1307, 1997.

9. C. Shu and S. P. Yam, "Effective generation of tunable single- and multiwavelength optical pulses from a Fabry-Perot laser diode", *IEEE Photonics Technol. Lett.*, vol. 9, pp. 1214-1216, 1997.

10. C. Shu and Y. C. Lee, "Tunable dual-wavelength picosecond optical pulses generated from a self-injection seeded gain-switched laser diode", *IEEE J. Quantum Electron.*, vol. 32, pp. 1976-1980, 1996.

11. Y. Zhao and C.Shu, "Single-mode operation characteristics of self-injection seeded Fabry-Perot laser diode with distributed feedback from a fiber grating", *IEEE Photonics Technol. Lett.*, vol. 9, pp. 1436-1438, 1997.

4 SPECTRALLY RESOLVED ANALYSIS OF FAST TUNING IN SINGLE-MODE PULSES GENERATED FROM MUTUALLY INJECTION-SEEDED FABRY-PEROT LASER DIODES

With the principle of mutual injection seeding described in *Section 2.2* of Chpater 2, electrically wavelength-tunable pulses are generated from two mutually injection-seeded Fabry-Perot laser diodes at 1 GHz. Using the spectrally resolved analysis, stable single-mode output is found to be obtained after four round-trip propagation cycles in the external cavity. We also probe the dynamic change of the spectrum during the switching between two single-mode wavelengths. It is found that the steady states can be reached after six to seven round-trip cycles.

This chapter is divided into three parts. *Section 4.1* gives an introduction about the principle of this experiment. *Section 4.2* contains the description of the experimental setup, as well as the discussion and the comments of the results. A brief summary of this experiment is stated in *Section 4.3.*

4.1 Introduction

Wavelength-tunable short pulses play an important role in multi-channel wavelength-division-multiplexing (WDM) communication systems. Some simple techniques of generating the pulses include self-injection seeding of a Fabry-Perot laser diode (FP-LD) [1], external injection-seeding of a FP-LD [2], and mutual injection-seeding of two FP-LDs [3]. Recent advances in WDM systems reveal the importance on the switching speed of the laser sources. Much research has been done to probe the dynamics of self-seeding from multi-mode to single-mode emission [4], from single-mode to another competing mode emission [5, 6], and switching between single-mode and dual-mode operations [7]. It was reported that stable pulse emissions can generally be achieved within five to ten round-trip cycles. The result promises a great potential in high speed wavelength switching compared with pulses generated from the mode-locking scheme [8].

Mutual injection seeding of two Fabry-Perot laser diodes (FP-LD) provides a ready and economic means to generate electrically tunable short pulses at a constant operating frequency [3]. A tuning range of 15 nm was previously reported. Since the tuning does not involve any mechanical adjustment, a stable and reproducible output can be obtained and a fast switching time is expected. In this chapter, we present an experimental study on the evolution dynamics of single-mode formation as well as the speed of wavelength switching. The result shows that the outputs are stabilized after four round-trip cycles in the former case, whereas six to seven cycles are required to complete the switching between two different wavelengths.

4.2 Experimental Details and Discussion

Fig. 4.1 shows the experimental setup. The output from the frequency synthesizer is split into two paths. One path is used to drive FP-LD1 directly, while the other path is directed to a tunable electrical delay before it is fed to FP-LD2. The laser diodes are synchronously driven at 1 GHz with about 20 dBm RF power applied to each device. A square-wave generator is connected to the frequency synthesizer to provide an amplitude modulation at 1 kHz.

The two FP-LDs are optically connected to form a common external resonance cavity. The devices operate under the condition of mutual pulse injection seeding. The continuous-wave (CW) threshold of FP-LD1 and FP-LD2 are 31.5 and 19.7 mA, and their mode spacing are 0.43 and 0.52 nm, respectively. The all-fiber external cavity consists of two polarization controllers (PC), two optical circulators (OC), one 70/30 coupler, 2670 m standard single-mode fiber (SMF), and 500 m dispersion compensating fiber (DCF). The SMF provides an anomalous dispersion on one side of the cavity, and the DCF on the other side provides an equal and opposite dispersion to the FP modes. Thus, the total round-trip propagation time is independent of the wavelength.

The evolution of single-mode pulses is described by the following sequence. In the first round-trip cycle, the multi-wavelength pulses emitted from FP-LD1 are directed by OC1 to the DCF. Owing to the group velocity dispersion, the pulses are stretched and the different wavelength components are temporally separated. The stretched

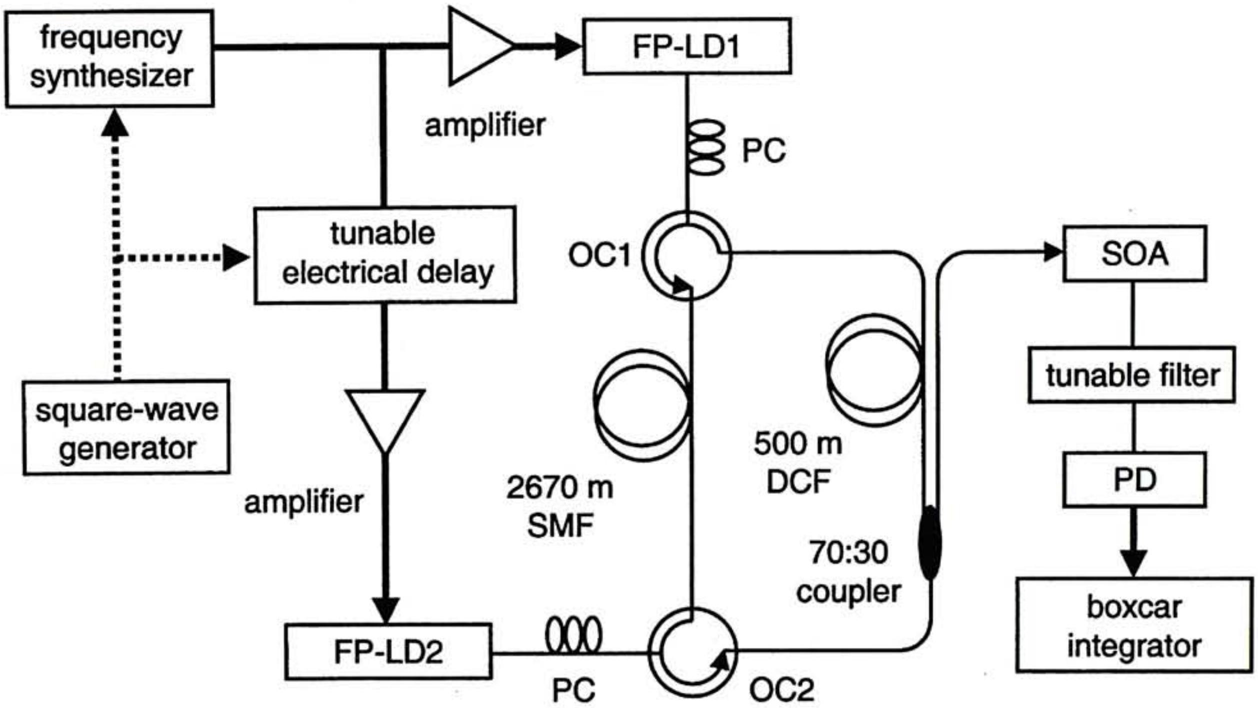

Fig. 4.1 Setup on the measurement of dynamics in mutually injection-seeded laser diodes. FP-LD1, FP-LD2: Fabry-Perot laser diodes; PC: polarization controller; OC1, OC2: optical circulators; SMF: single-mode fiber; DCF: dispersion compensating fiber; SOA: semiconductor optical amplifier; PD: photodetector.

pulses then follow the path through OC2 to FP-LD2. Since the pulses are dispersed, only a certain wavelength component will arrive at FP-LD2 at the moment just before the laser reaches threshold. Thus, the wavelength will experience a higher gain and grows rapidly during the pulse build-up time. The output pulses from FP-LD2 are then directed to the SMF and propagates to FP-LD1. With a proper choice of the RF driving frequency that matches closely with a harmonic of the cavity round-trip propagation frequency, the same wavelength component will also arrive at FP-LD1 just before it reaches threshold. This mutual injection-seeding mechanism goes on until the selected wavelength dominates other components and results in a single-mode oscillation. By adjusting the tunable electrical delay between the RF driving signals, one can select the output wavelength without changing the operating frequency. It is worth noting that the wavelength selection process does not depend on any kind of mechanical adjustment.

The steady-state outputs are investigated using an optical spectrum analyzer of 0.1 nm resolution and a 32 GHz photodetector together with a digital sampling oscilloscope. Fig. 4.2(a) shows the output single-mode spectrum and the corresponding light pulses. The peak wavelength is located at 1529.8 nm (λ_1) with a SMSR of about 20 dB. The pulse width is 75 ps and the peak power is 0.38 mW. The measured spectral width is 0.47 nm. By adjusting the electrical delay, the output wavelength can be tuned to another value. Fig. 4.2(b) shows the spectrum and the corresponding pulses after the wavelength tuning. The peak wavelength is now located at 1533.8 nm (λ_2) with a SMSR of about 20 dB. The pulse width and the peak power are 78 ps and 0.36 mW, respectively, and the spectral width is 0.49 nm.

Another experiment is to investigate the evolution dynamics as the laser pulses develop gradually from a multi-mode background into a single-mode output. To switch between multi-wavelength and single-wavelength oscillations, one can simply modulate the amplitude of the electrical signal from the frequency synthesizer using the square-wave generator. The resultant waveform becomes a 1 GHz sinusoidal signal turning on and off at 1 kHz. The external cavity length is about 3180 m, corresponding to a round-trip propagation time of 16 μs. Since both the rise time and the fall time of the square wave envelope are shorter than 0.01 μs, the rising and falling edges will not affect the results significantly. The output port is connected to

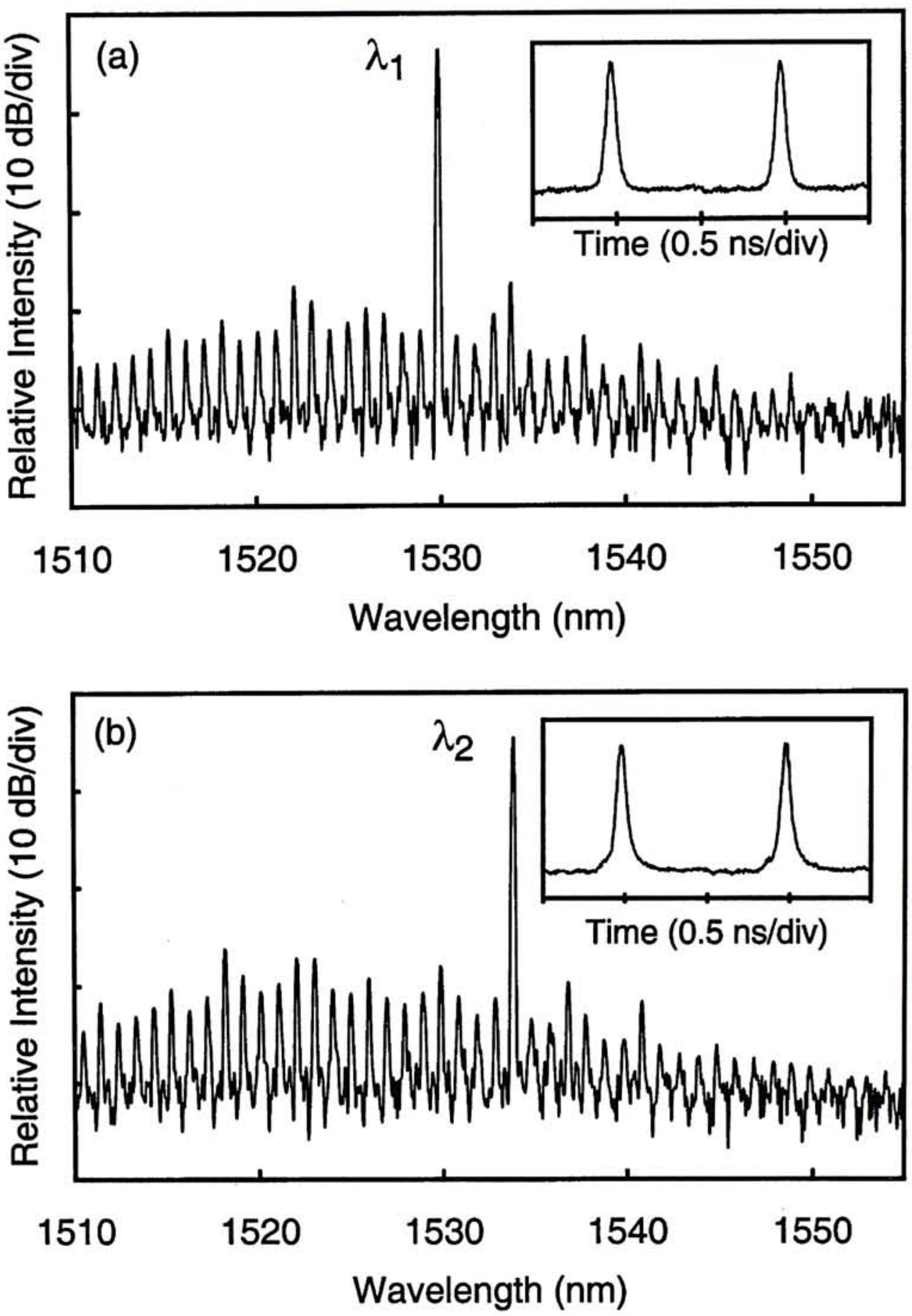

Fig. 4.2 *Output spectra and the corresponding pulses (a) wavelength selection at λ_1=1529.8 nm. (b) wavelength selection at λ_2=1533.8 nm.*

a semiconductor optical amplifier (SOA) for signal enhancement. The amplified output is then analyzed using an electrically tunable F-P filter and a 32 GHz photodetector (PD) connected to a boxcar integrator. The gating window of the boxcar integrator is set to be 15 μs to ensure that the detected signal pulses are within the same round-trip propagation cycle. After obtaining the spectral characteristic of a specific cycle, the delay time of the gate is increased in steps of 16 μs to reveal the spectrum in the following cycles before a steady state is reached.

When the RF signal is switched on, the laser diodes will initially operate at a multi-mode state. Within the first 16 μs (0^{th} round-trip), a selected wavelength from FP-LD1 will arrive at FP-LD2 during its pulse build-up time. The wavelength component is amplified and is then directed to FP-LD1 through the SMF. In the next 16 μs, the wavelength is further enhanced by the two FP-LDs and a single-mode characteristic begins to develop. The process repeats in the following round trips until a stable single-wavelength operation is obtained. Fig. 4.3 depicts the output spectra in the first few round trips when the laser diodes are switched from multi-mode to single-mode operation at 1529.8 nm (λ_1). The plots show the gradual buildup of a single-mode characteristic with increasing round-trip cycle number. A steady state output is observed after four round trips. Note that since the bandwidth of the tunable filter is 0.65 nm, the spectral resolution of the plots is lower than that in Fig. 4.2.

Compared to previous reports on the dynamics of self-seeded laser diodes [4], the single-mode state is reached slightly faster in the present scheme of mutual injection seeding. The observation is attributed to the two-fold enhancement of the selected wavelength and suppression of the multi-mode background in each round-trip cycle.

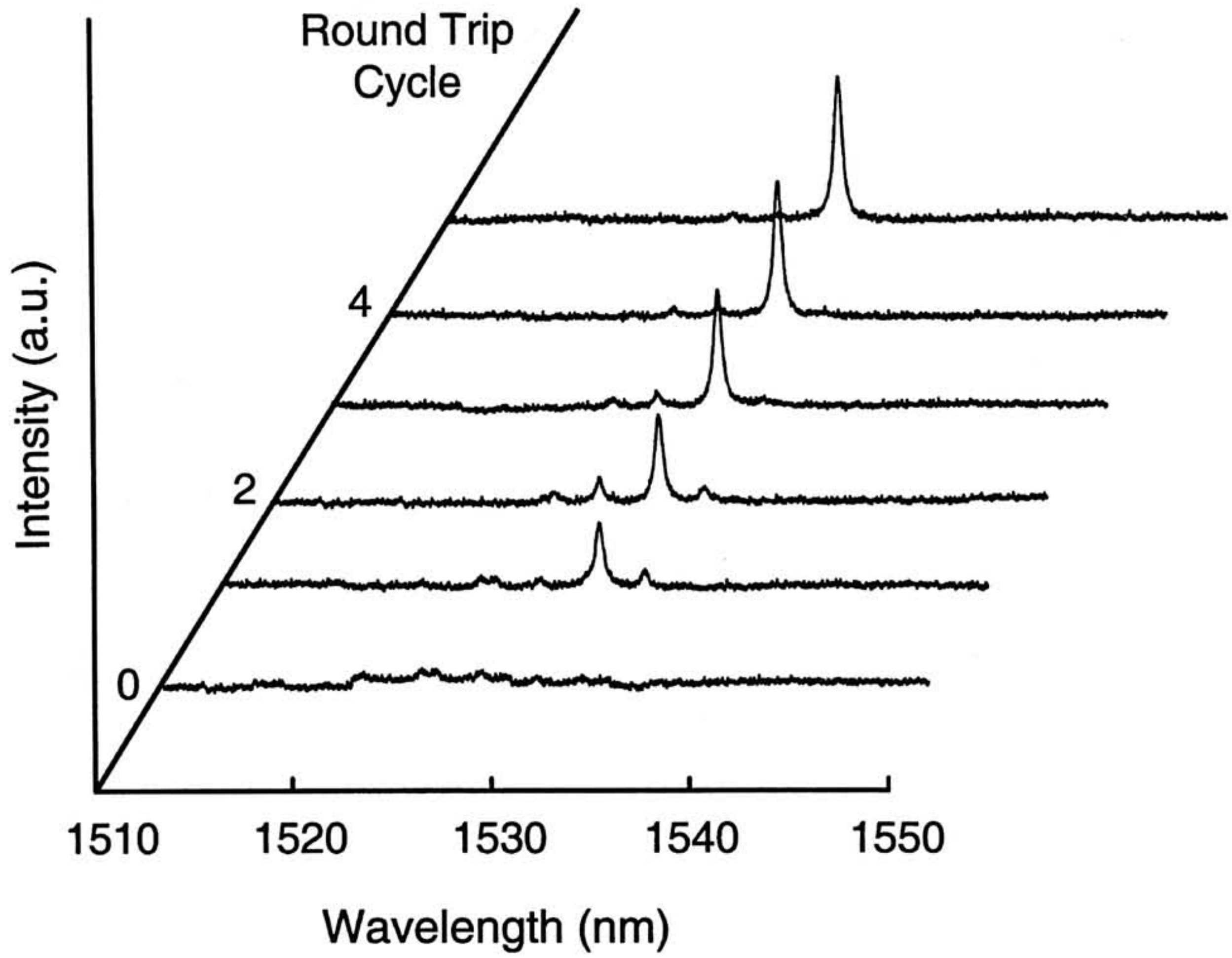

Fig. 4.3 *Evolution of the output spectrum from multi-mode operation to single-mode operation.*

The dynamic behavior when the output wavelength is switched between λ_1 and λ_2 is also investigated. The square-wave generator is now used to modulate the tunable electrical delay. Thus, the delay time between the two RF signals is periodically changed at 1 kHz. Fig. 4.4 shows the spectral evolution as the output wavelength of the laser diodes changes from λ_1 to λ_2. The laser diodes take seven round trips to yield a stable output. The speed is slightly slower than that of single-mode pulse formation from a multi-mode background. In this experiment, a relatively large portion of λ_1 remains in the output pulses during the first few round trips. Thus, the gain at λ_2 is suppressed, leading to a longer build-up time. During the transition, we

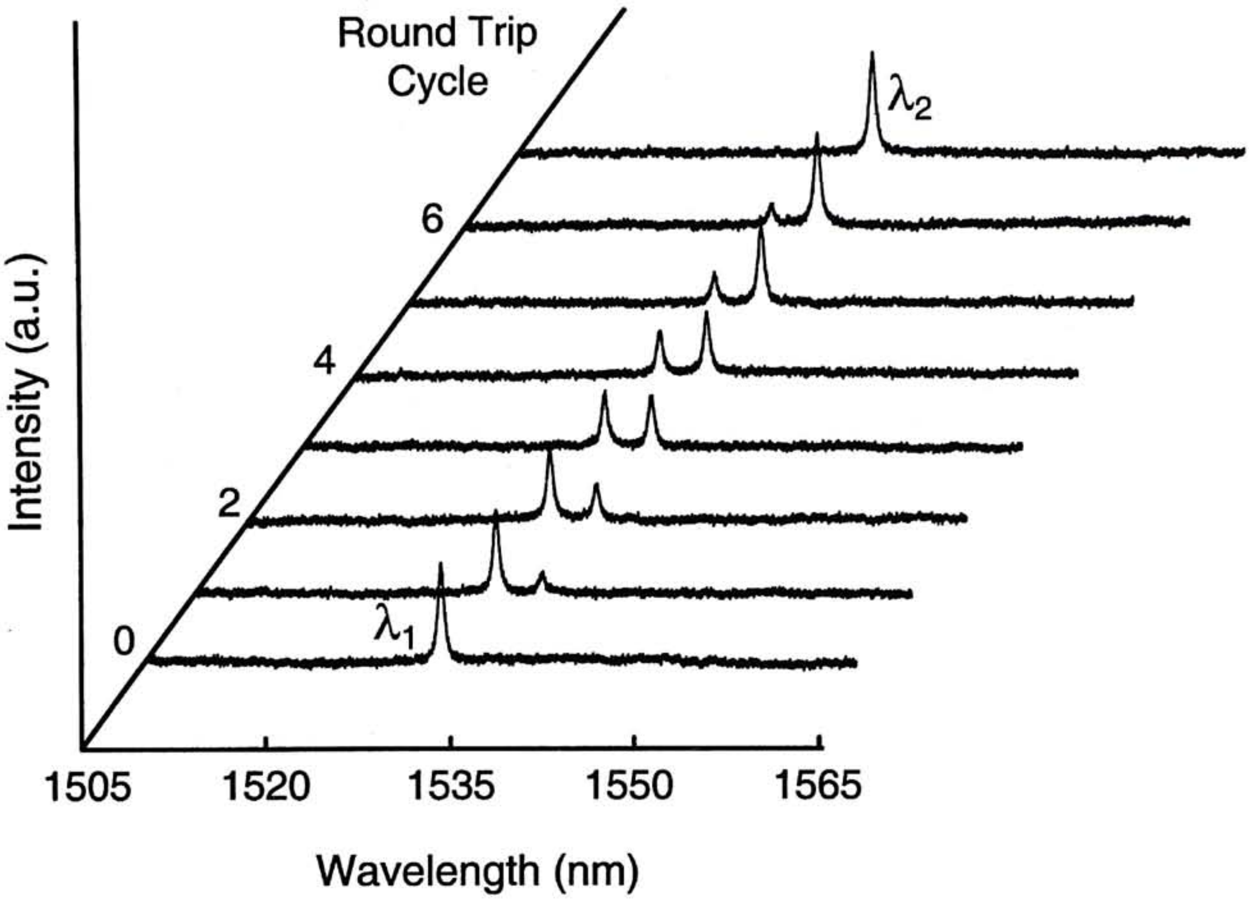

Fig. 4.4 *Dynamic change of the spectrum during wavelength switching from λ_1=1529.8 nm to λ_2=1533.8 nm.*

also find that the laser diodes are temporally in dual-mode operation in about the third and the forth round-trip cycle.

Fig. 4.5 shows the evolution of the output spectrum as the operating wavelength is changed back from λ_2 to λ_1. Here, the laser diodes take six round trips to stabilize. The switching speed is slightly faster than that from λ_1 to λ_2. The minor improvement in speed is attributed to the closeness of λ_1 to the gain peak of the laser diodes. Thus, the build-up of the optical power at λ_1 is faster than that at λ_2.

It is expected that a larger tuning range can be obtained by using two laser diodes with similar mode spacings and spectral characteristics. However, as the tunable

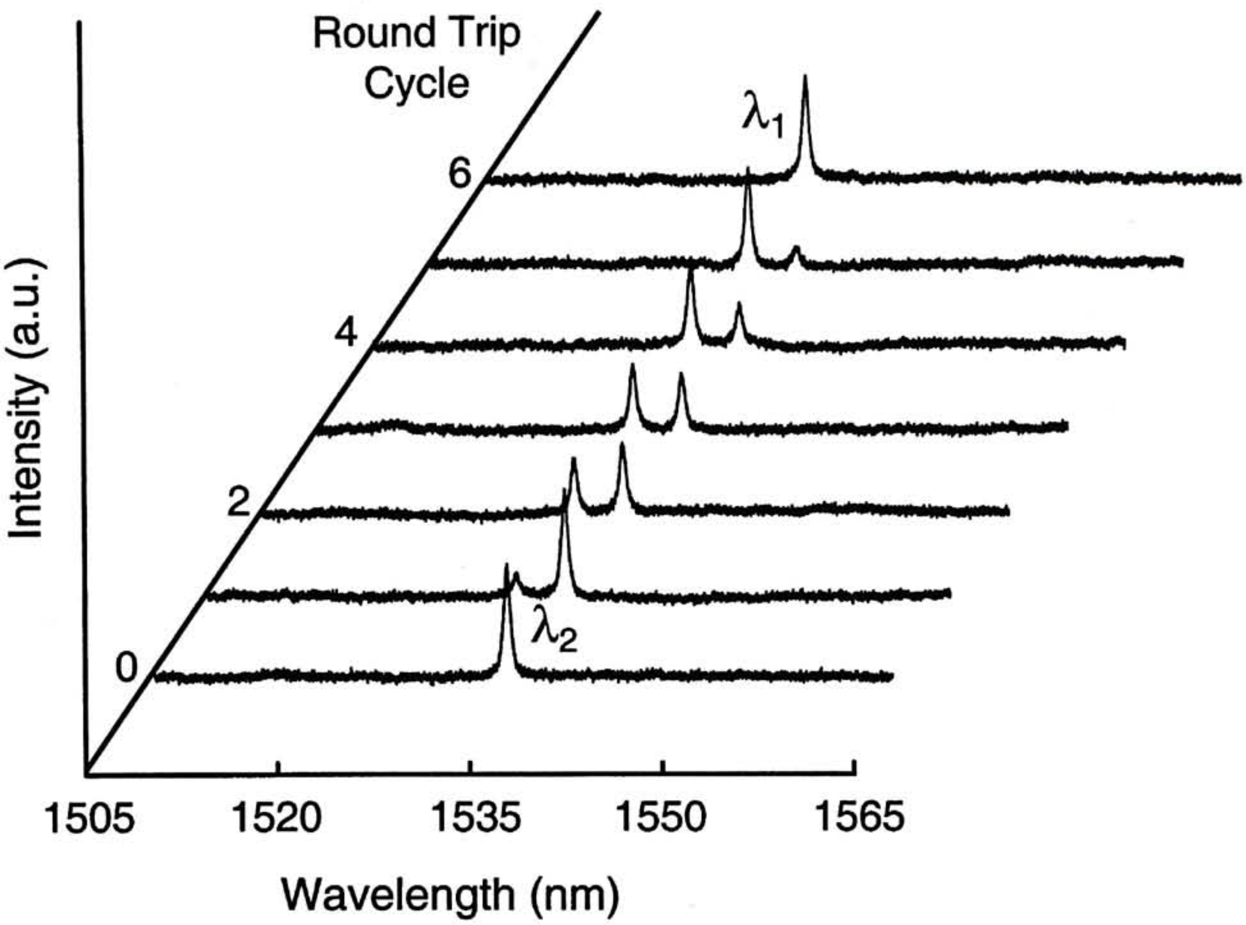

Fig. 4.5 *Dynamic change of the spectrum during wavelength switching from λ_2=1533.8 nm to λ_1=1529.8 nm.*

output will have a smaller neighboring mode separation, a larger dispersion will be needed to achieve single-wavelength oscillation. Hence, longer single mode fiber and dispersion compensated fiber are required in the setup, thus causing instability in the output.

The length of the external cavity will pose a limit on the speed of the wavelength switching. To shorten the cavity, the SMF and the DCF can be replaced by a single piece of chirped fiber grating. Depending on the input and output ports, the chirped grating can provide either a positive or a negative group velocity dispersion. An alternative method is to use a fiber imprinted with Bragg gratings at different wavelengths along its length. Wavelength switching can thus be achieved in a relatively short cavity [9]. The cavity can be adopted for use in a fiber laser or in mutually injection-seeded semiconductor lasers.

4.3 Summary

In summary, mutual pulse injection seeding of Fabry-Perot laser diodes provides a fast and effective way to generate electrically tunable single-mode pulses at a constant frequency. The time required to obtain a single-mode output from a multi-mode background is experimentally determined to be four round-trip cycles. To complete the switching between two different wavelengths, about six to seven round-trip cycles are needed. The results consistently show a fast response and promise a good potential for high-speed wavelength switching.

Reference

1. M. Cavelier, N. Stelmakh, J. M. Xie, L. Chusseau, J.-M. Lourtioz, C. Kazmierski and N. Bouadma, "Picosecond (<2.5 ps) wavelength-tunable (~ 20 nm) semiconductor laser pulses with repetition rates up to 12 GHz", *Electron. Lett.*, vol. 28, pp. 224-226, 1992.
2. D-S Seo, H. F. Liu, D. Y. Kim, and D. D. Sampson, "Injection power and wavelength dependence of an external-seeded gain-switched Fabry-Perot laser", *Appl. Phys. Lett.*, vol. 67, pp. 1503-1505, 1995.
3. K. Chan and C. Shu, "Electrically wavelength-tunable pulses generated by synchronous two-way injection seeding", *IEEE Photonics Technol. Lett.*, vol. 11, pp. 170-172, 1999.
4. D. Huhse, M. Schell, W. Utz, J. Kaessner, and D. Bimberg, "Dynamics of single-mode formation in self-seeded Fabry-Perot laser diodes", *IEEE Photonics Technol. Lett.*, vol. 7, pp. 351-353, 1995.
5. D. Huhse, M. Schell, W. Utz, and D. Bimberg, J. A. R. Williams, L. Zhang, and I. Bennion, "Fast wavelength switching of semiconductor laser pulses by self-seeding", *Appl. Phys. Lett.*, vol. 69, pp. 2018-2020, 1996.
6. D. Huhse and D. Bimberg, "Competing mode suppression ratio of electrically wavelength tunable self-seeding lasers", *IEEE Photonics Technol. Lett.*, vol. 11, pp. 167-169, 1999.

7. K. K. Chow and C. Shu, "Switching dynamics between single-mode and dual-mode pulse emissions from a self-seeded laser diode", *Appl. Phys. Lett.*, vol. 76, pp. 276-278, 2000.

8. P. A. Morton, R. J. Helkey, J. E. Bowers, "Dynamic detuning in actively mode-locked semiconductor lasers", *IEEE J. Quantum Electron.*, vol. 25, pp. 2621-2633, 1989.

9. K. Chan and C. Shu, "Electrical switching of wavelength in actively modelocked fibre laser incorporating fibre Bragg gratings", *Electron. Lett.*, vol. 36, pp. 42-43, 2000.

5 FAST SPECTRAL IMPROVEMENT IN GAIN-SWITCHED PULSES GENERATED FROM A DISTRIBUTED FEEDBACK LASER DIODE USING A LOOSELY COUPLED EXTERNAL CAVITY

Based on the idea mentioned in *Section 2.3* of Chapter 2, a simple external cavity is constructed to provide adjustable feedback to a gain-switched distributed feedback laser diode. A 27 dB enhancement in the side-mode suppression ratio (SMSR) and a 0.3 nm reduction in the spectral linewidth have been observed. The improvement shows a saturation behavior when the feedback power reaches about -16 dBm. We report on the evolution and the dynamics of the spectral improvement. The steady state can be achieved as soon as four round-trip feedback cycles are completed. Dependencies of the speed of improvement and the SMSR on the feedback pulse arrival time are also investigated. The optimal result can be obtained over a sensitive time window of about 20 ps.

This chapter is divided into three parts. *Section 5.1* is the introduction of this work. *Section 5.2* contains the experimental setup with the discussion and the comments of the results. A brief summary of this experiment is given in *Section 5.3*.

5.1 Introduction

Gain-switching of a distributed feedback (DFB) laser diode is a simple and efficient method to generate single-wavelength short pulses and is widely used in ultra-fast optical switching, soliton transmission, and time-division-multiplexed communication systems. Much research has been focused on the reduction of timing jitter in DFB lasers using external continuous wave (CW) light injection [1, 2] or pulsed optical feedback [3, 4]. It is also noted that the spectral quality of the output pulses is often degraded by gain-switching. The large fluctuation of the carrier density in the gain-switching process causes excitation of the other side modes [5]. Frequency chirp is also introduced in the laser output. These problems will lead to a degradation of the side-mode suppression ratio (SMSR) and result in spectral width broadening of the output pulses. The mode partition noise will also be increased and thus affecting the signal-to-noise ratio and increasing the error rate of transmission.

To solve these problems, a simple method is to adopt an external cavity to provide adjustable feedback to the DFB laser [3]. The cavity can be constructed in different configurations. However, a general limitation is that the pulse repetition rate is tied to the length of the cavity. In this paper, we present a configuration in which the cavity length can be easily controlled with high precision to facilitate operation at any arbitrary rate. The setup is also relatively simple and thus can produce pulses with stable temporal profiles and spectral characteristics. We find that the SMSR can be dramatically improved by 27 dB while in the spectral width is reduced by 0.3 nm. For the first time, the dynamics of spectral improvement is investigated. The experimental results show that a stable output can be obtained as soon as four round-trip feedback cycles are completed in the cavity.

5.2 Experimental Details and Discussion

Fig. 5.1 shows the experimental setup. The laser source is a 1.55 μm DFB laser diode with 23 mA cw threshold current. The laser diode is biased below threshold at 14 mA and is gain-switched with a 24 dBm sinusoidal signal at 1 GHz. The output peak power is 7 mW and the pulse width is 39 ps. The external cavity contains a 70/30 coupler, a polarization controller (PC), a 100 m long dispersion shift fiber (DSF), a variable optical delay, a variable optical attenuator and an optical mirror. The emitted gain-switched pulses will propagate in the external cavity and reflect back to the laser diode. The PC is used here to maintain the same polarization between the emitted and the reflected pulses. To modify the output characteristics, the reflected pulses should arrive at the laser diode just before it reaches threshold. Therefore, the

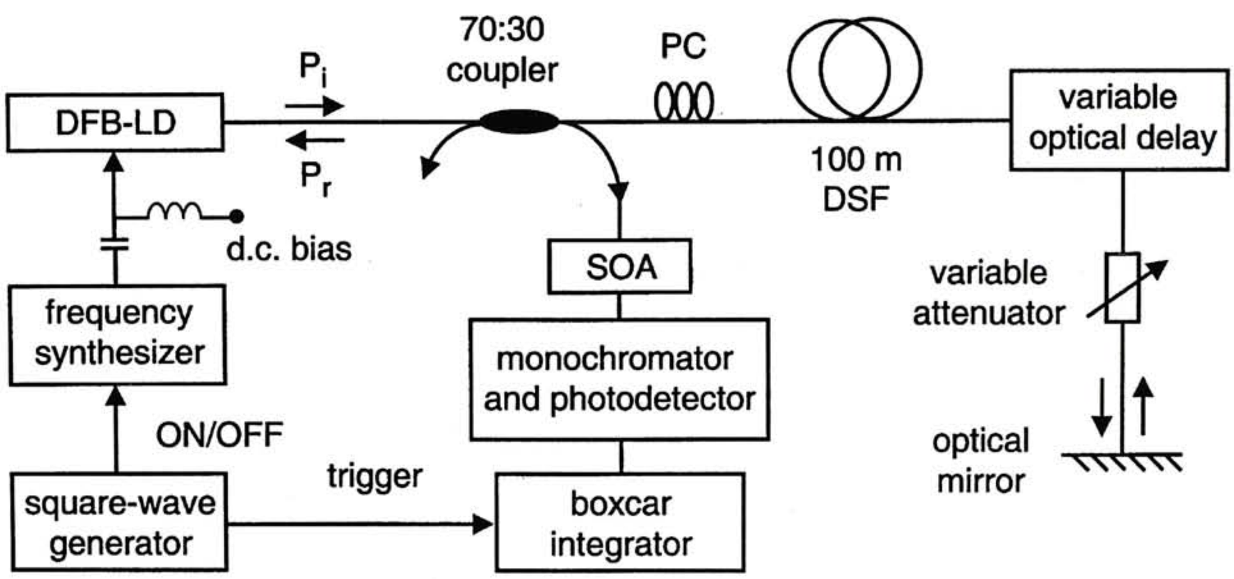

Fig. 5.1 *Setup on the measurement of the dynamic behavior of a gain-switched DFB laser diode in a loosely coupled external cavity. DFB-LD: distributed feedback laser diode; PC: polarization controller; DSF: dispersion shifted fiber; SOA: semiconductor optical amplifier.*

variable optical delay is used to adjust the cavity length with high precision so that the laser diode can operate at any arbitrary repetition rate. The variable attenuator serves the purpose of changing the optical feedback ratio in order to study its effect on the output performances. The 30% port of the coupler serves as the laser output and the steady-state output is investigated using an optical spectrum analyzer of 0.1 nm resolution and a 32 GHz photodetector together with a digital sampling oscilloscope (not shown in Fig. 5.1).

Fig. 5.2 shows the dependence of the output SMSR and the spectral width on the feedback power. As the feedback is increased from –22 dBm to –16 dBm, the SMSR changes from 8 dB to 35 dB, corresponding to a 27 dB improvement. Also, the

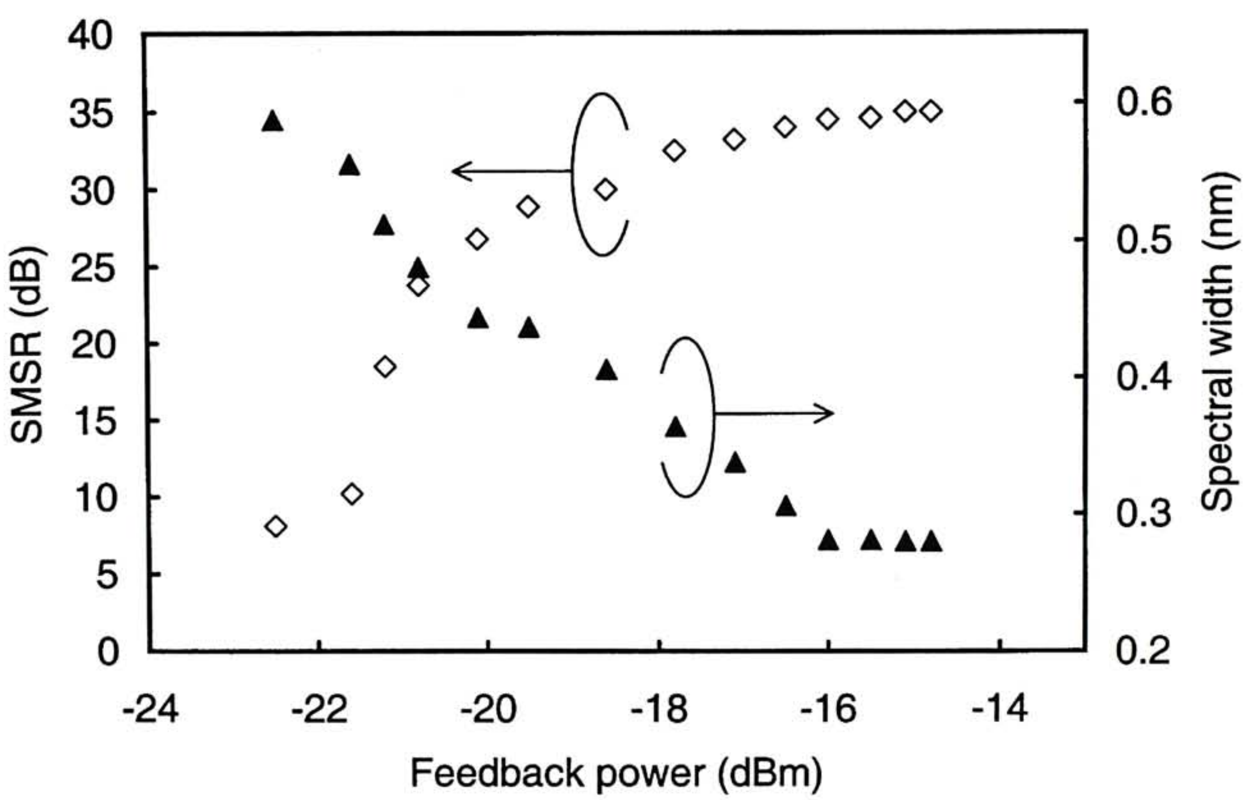

Fig. 5.2 *Dependence of the output SMSR and the spectral width on the feedback power.*

output spectral width is changed from 0.58 to 0.28 nm with a total reduction of 0.3 nm. The observation indicates that the optimized feedback power is about –16 dBm for the spectral improvement. Further increase of the feedback power will not result in additional improvement of the spectral characteristic, but causing a wider output pulse width and a poorer time-bandwidth product. As the laser diode is gain-switched with a large RF power (+24 dBm), the large fluctuation of the carrier density in the active region will result in a degradation of the output SMSR and give rise to spectral width boardening through the occurrence of frequency chirp. The reflected pulses from the external cavity help to maintain a higher spectral power of the main mode and increase its gain; thus, other side modes are suppressed.

Fig. 5.3(a) shows the steady-state output spectrum and the corresponding light pulses without feedback. The peak wavelength is located at 1547.7 nm with a pulse width of 39 ps. The SMSR is degraded substantially from cw operation at 34 dB to 8 dB in pulse operation. The measured 3-dB spectral width is 0.59 nm. Fig. 5.3(b) shows the output spectrum and the corresponding light pulses with a –16 dBm feedback power and an optimized optical delay. A dramatic improvement of the SMSR to 35 dB is obtained. Also, the 3-dB spectral width is reduced to 0.28 nm. The spectral characteristics are comparable with those under cw operation. Owing to a smaller overshoot of the carrier density, the output pulse width is increased to 57 ps. The pulses can be further compressed to 28 ps with a suitable length of dispersion compensating fiber.

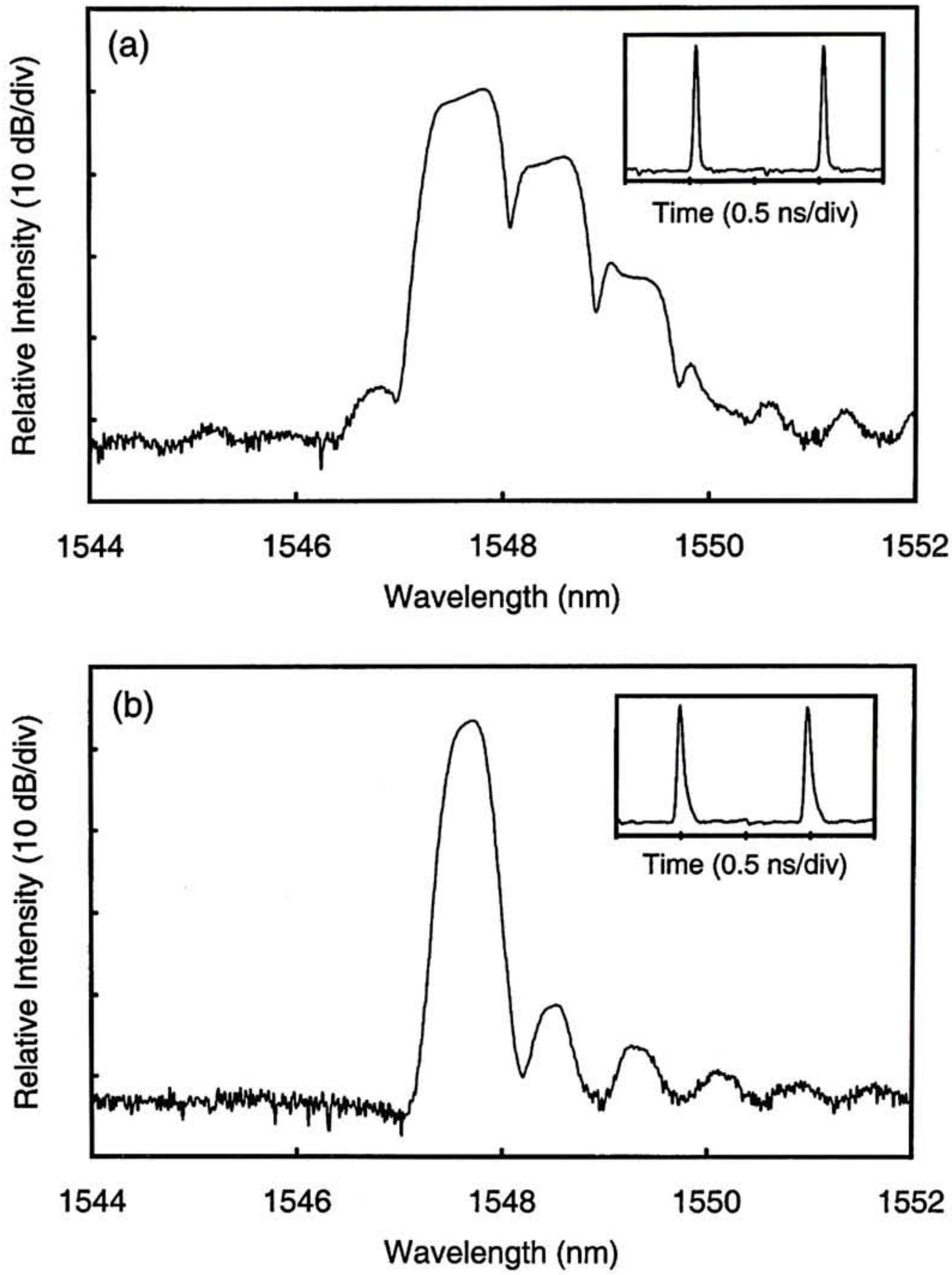

Fig. 5.3 *Output spectra with (a) no feedback and (b) –16 dBm feedback. The insets show the corresponding pulses.*

Another experiment is to investigate the evolution dynamics as the DFB laser output is gradually improved by the reflected pulses. The 30% output port is now connected to a semiconductor optical amplifier (SOA) for power enhancement as shown in Fig. 5.1. The amplified light then passes through a tunable monochromator for the measurement of the evolution of different wavelength components. The light pulses are detected by a 32 GHz photodetector and the signal is fed to a boxcar integrator. A square wave generator is connected to the frequency synthesizer and is used to switch on and switch off the output signal for the time-resolved analysis. As the square wave generator operates at 10 kHz with a 50% duty cycle, the modulated waveform contains a 1 GHz sinusoidal signal turning on and off periodically at 10 kHz. Since the rise and fall times of the square wave generator are shorter than 10 ns, the transients will not adversely affect the result. The 100 m DSF is employed in the external cavity to increase the round-trip propagation time to 1 μs. Hence, the gate width of the boxcar integrator can be set to 0.9 μs to ensure that the gated signal only contains pulses in the same round-trip cycle.

When the RF signal is turned on, the output from the DFB laser diode will remain unchanged in the subsequent 1 μs duration (0th round trip). In the next 1 μs (1st round trip), the laser diode characteristics will begin to be modified by the reflected pulses. Thus, the spectral power of the main mode starts to grow and the side modes are suppressed. The spectral characteristic in each round-trip cycle can be studied by sweeping the tunable monochromator. After the data is collected by the boxcar integrator, the delay of the gate is increased by 1 μs to study the characteristic of the next round-trip cycle. The process repeats in the following few round trips until a steady output is achieved. Fig. 5.4 shows the output spectra in the first few round-trip cycles when the laser diode is subjected to the feedback. The result shows the gradual change of the output spectrum. Both an increase of the SMSR and a

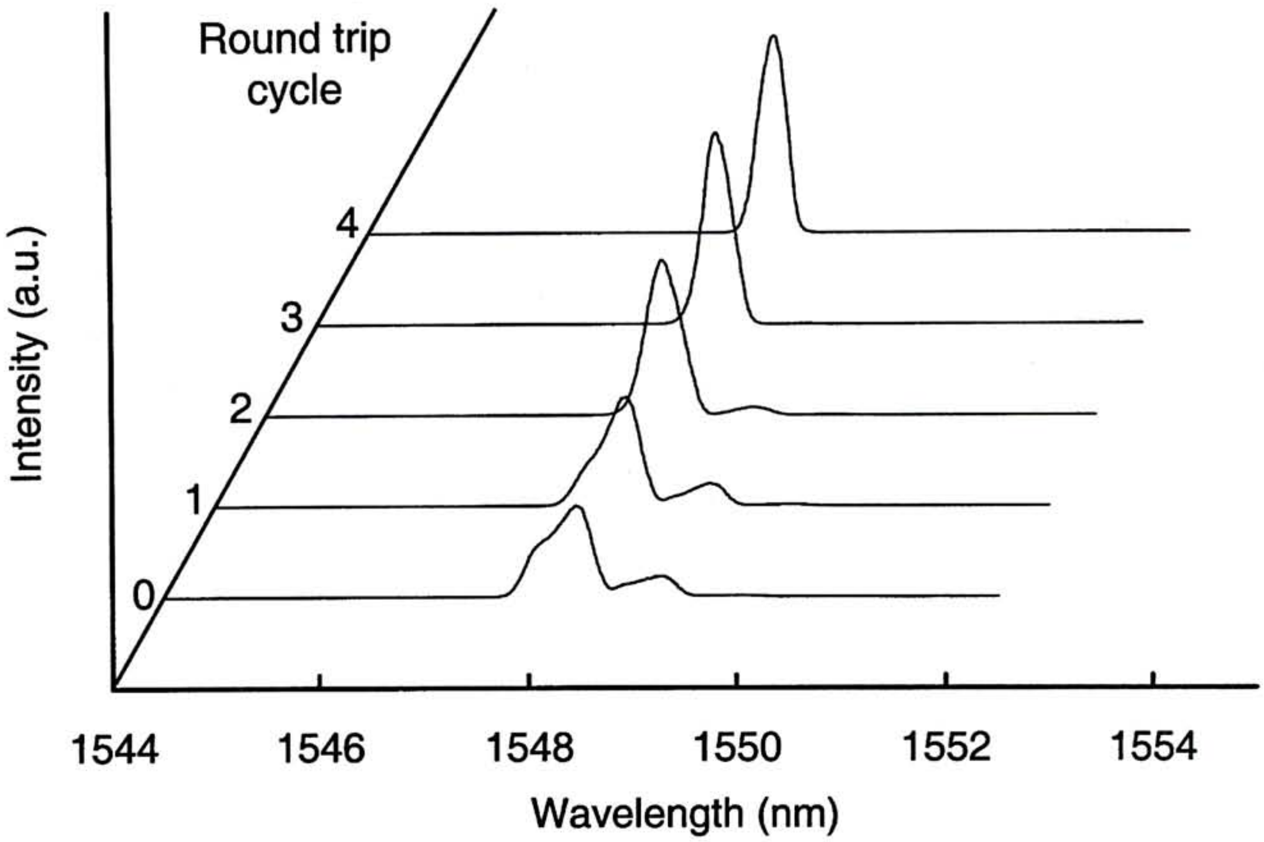

Fig. 5.4 *Evolution of the output spectrum in the first few round-trip cycles of the feedback pulses.*

reduction of the spectral width are observed with increasing round-trip cycles. A stable output is obtained after four round trips, promising a potential for fast improvement of the output characteristics.

The feedback pulse arrival time plays a critical role in determining the output characteristics. The effect can be studied by adjusting the variable optical delay in the external cavity. Fig. 5.5 shows the round-trip cycles required to stabilize the output against the pulse arrival time. The dependence of the SMSR is also shown. The 0 ps delay time sets the reference for the optimal delay. For improvement of the spectral characteristics, the reflected pulses should arrive at the laser diode just before it reaches threshold. Detuning of the pulse arrival time will affect the number

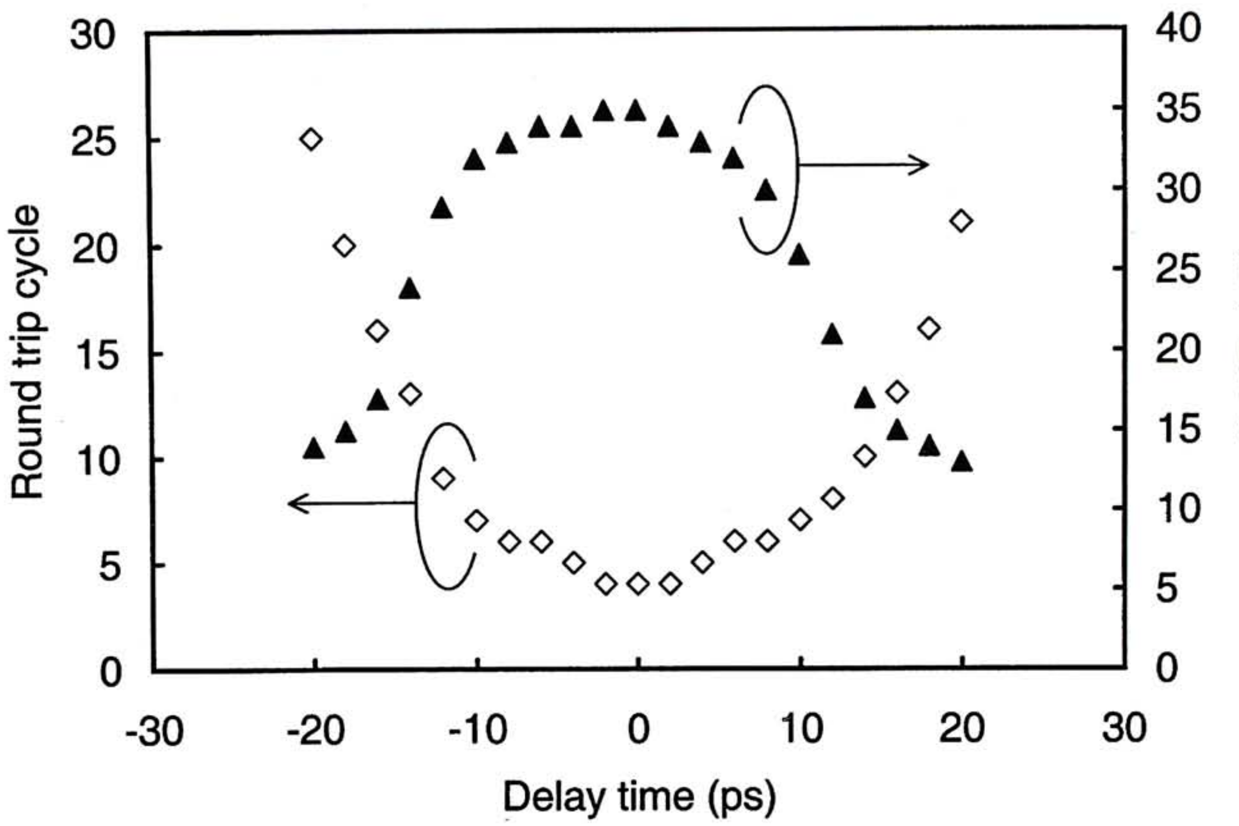

Fig. 5.5 *Plot of the number of round-trip cycles needed to achieve a steady state output and the SMSR against the arrival time of the reflected pulses.*

of round-trip cycles needed to achieve a stable output. Also, the output SMSR will be degraded. The result shows that within a delay range of –10 ps to +10 ps, the laser maintains a SMSR over 30 dB while only a few round-trip cycles are needed for stabilizing the output. Thus, it is concluded that the sensitive time-window for the feedback to take effect is about 20 ps. Outside this range, both the round-trip number and the SMSR suffer a great degradation and only a minor spectral improvement can be obtained.

With the variable optical delay, the repetition rate of the laser pulses is no longer tied by the external cavity length. To have the laser diode operated at another repetition rate, one can simply tune the frequency synthesizer and the variable optical delay in synchronization. Since the resolution of the delay is 1 ps, the sensitive time-window for feedback can be precisely matched at any arbitrary repetition rate in our configuration.

5.3 Summary

In summary, a significant spectral improvement is obtained in a gain-switched DFB laser diode using a simple external cavity to provide adjustable optical feedback pulses. The side-mode suppression ratio shows a 27 dB improvement and the spectral width is reduced 0.3 nm. The time required to achieve a stable output is experimentally determined to be as fast as four round-trip cycles, and is dependent upon the arrival time of the feedback pulses. The result shows the potential of fast output stabilization of the DFB laser under optical feedback.

Reference

1. D. S. Seo, D. Y. Kim, and H. F. Liu, "Timing jitter reduction of gain-switched DFB laser by external injection-seeding", *Electron. Lett.*, vol. 32, pp. 44-45, 1996.

2. P. Gunnung, et al, "Gain-switched DFB laser diode pulse source using continuous wave light injection for jitter suppression and an electroabsorption modulator for pedestal suppression", *Electron. Lett.*, vol. 32, pp. 1010-1011, 1996.

3. L. P. Barry, J. Debeau, and R. Boittin, "Simple technique to improve the spectral quality of gain-switched pulses from a DFB laser", *Electron. Lett.*, vol. 30, pp. 2143-2145, 1994.

4. R. Calvani, F. Cisternino, R. Girardi, and M. Puleo, "All fibre self injection seeding for timing jitter reduction in a chirp compensated gain-switched DFB laser", in *Proc. ECOC '98*, vol. 1, pp. 167-168, 1998.

5. D. Marcuse and T. P. Lee, "On approximate analytical solutions of rate equations for studying transient spectra of injection lasers", *IEEE J. Quantum Electron.*, vol. 19, pp. 1397-1406, 1983.

6 CONCLUSION AND FUTURE WORK

In this chapter, a conclusion of this thesis is made in *Section 6.1*. The possible future work is included in *Section 6.2*.

6.1 Conclusion

In conclusion, fast wavelength selection and switching of short pulses are successfully demonstrated with self-seeding and mutually injection seeding schemes. Also, fast spectral improvement of distributed feedback laser is achieved with adjustable optical feedback.

With the self-seeding scheme, fast switching between single- and dual-wavelength operations of a Fabry-Perot laser diode is demonstrated in a fiber-optic external cavity at a constant operating frequency. The side-mode-suppression-ratio is maintained at about 20 dB in both cases. The time required to achieve stable operation is experimentally determined to be about five to six round trips. The result shows that fast switching in the order of nanoseconds is possible using a fiber cavity of a few centimeters.

The mutual pulse injection-seeding of two Fabry-Perot laser diodes provides a fast and effective way to generate electrically tunable single-mode pulses at a constant frequency. The time required to obtain a single-mode output from a multi-mode background is experimentally determined to be four round-trip cycles. To complete the switching between two different wavelengths, about six to seven round-trip cycles are needed. The results consistently show a fast response and promise a good potential for high-speed wavelength switching.

With a simple external cavity to provide adjustable optical feedback pulses, a significant spectral improvement is obtained in a gain-switched DFB laser diode. The side-mode suppression ratio shows a 27 dB improvement and the spectral width is reduced by 0.3 nm. The time required to achieve a stable output is experimentally determined to be as fast as four round-trip cycles, and is dependent upon the arrival time of the feedback pulses. The result shows the potential of fast output stabilization of the DFB laser under optical feedback.

6.2 Possible Future Work

Based on the results and observations from this thesis, there are two areas of further work worthy to be considered.

1. For the mutual injection seeding approach described in Chapter 5, the FP-LD2 can be replaced by an optical modulator to form a self-seeding scheme [1] as shown in Fig. 6.1. With different bias conditions we find that either self-seeded pulses or mode-locked pulses can be obtained. By the spectrally resolved analysis the switching dynamics under different bias conditions can be investigated. Also, fast switching between two different schemes can be studied by modulating the bias current.

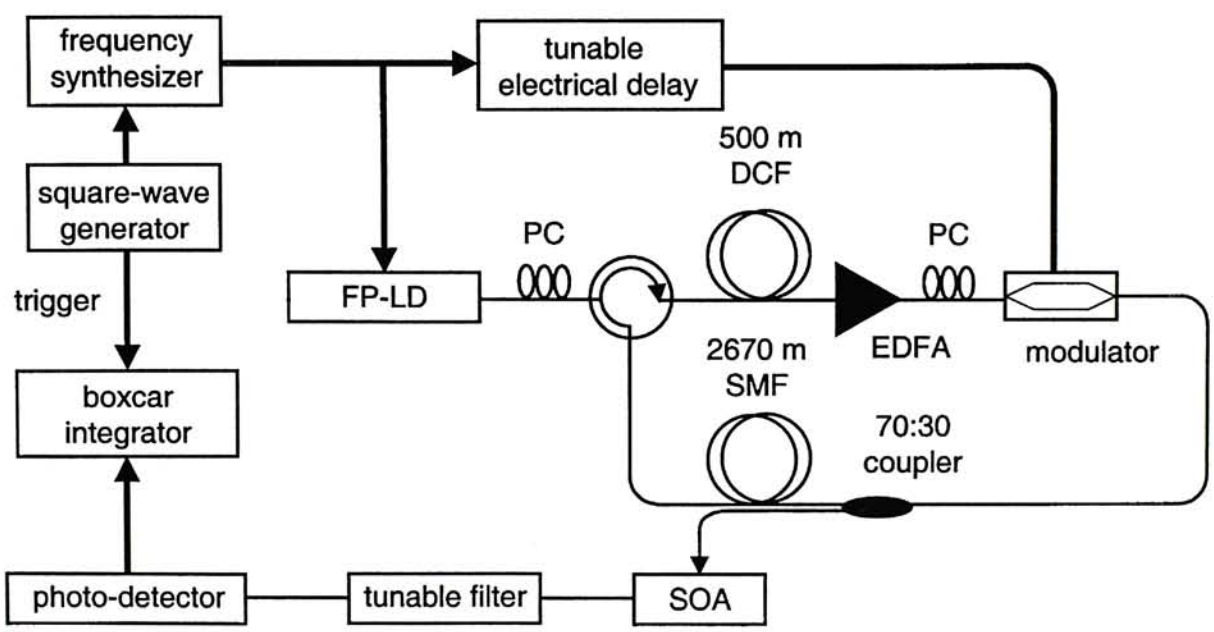

Fig. 6.1 *Setup on the measurement of the transient dynamics of a self-seeded or mode-locked laser diode. FP-LD: Fabry-Perot laser diode; PC: polarization controller; DCF: dispersion compensated fiber; SMF: single-mode fiber; SOA: semiconductor optical amplifier.*

2. In the mutual injection seeding scheme, the two pieces of fibers can be replaced by fiber gratings [2]. Thus, the pulse propagation time for one round trip can be reduced. Compared with the original scheme using fibers, this approach is expected to have wavelength switching in the nano-second range and is worthy to have further investigation.

Reference

1. K. Chan and C. Shu, "Electrically wavelength-tunable picosecond pulses generated from a self-seeded laser diode using a compensated dispersion-tuning approach", *IEEE Photon. Technol. Lett.*, vol. 11, pp.1093-1095, 1999.

2. K. Chan and C. Shu, "Electrical switching of wavelength in actively modelocked fibre laser incorporating fibre Bragg gratings", *Electron. Lett.*, vol. 1, pp. 42-43, 2000.

APPENDIX

Appendix A. List of Publications

1. K. K. Chow and C. Shu, "Switching dynamics between single-mode and dual-mode pulse emissions from a self-seeded laser diode", *Applied Physics Letters*, vol. 76, pp. 276-278, 2000.

2. K. K. Chow and C. Shu, "Dynamics of switching between single-mode and dual-mode oscillations of a self-seeded laser diode", *Proc. IEEE LEOS '99*, Nov. 99, paper ThI4.

3. K. K. Chow and C. Shu, "Spectrally resolved analysis of fast tuning in single-mode pulses generated from mutually injection-seeded Fabry-Perot laser diodes", accepted by *IEEE Photonics Technology Letters*, June.

4. K. K. Chow and C. Shu, "Fast spectral improvement in gain-switched pulses generated from a distributed feedback laser diode using a loosely coupled external cavity", submitted to *IEEE Photonics Technology Letters*.

5. K. K. Chow and C. Shu, "Dynamics of Wavelength tuning in Optical Pulses Generated from Two-Way Injection-Seeded Laser Diodes", *IEEE Hong Kong MTT/AP/LEOS Postgraduate Conference*, Sept. 2000.

Appendix B. Modeling of Self-Seeded Fabry-Perot Laser

This modeling work is collaborated with an undergraduate student. [1]

The rate of change of the carrier number and the photon number inside the laser cavity can be described by the rate equations:

$$\frac{dN}{dt}=\frac{I}{q}-\frac{N}{\tau_s}-\sum_i \Gamma v_g g_i S_i \tag{A1}$$

$$\frac{dS_i}{dt}=\left[\Gamma v_g g_i-\frac{1}{\tau_p}\right]S_i+\frac{\beta N}{\tau_s} \tag{A2}$$

where N is the carrier number and S is the photon number, and the definitions of the symbols are stated in Table 3.1.

To perform the numerical analysis on the self-seeding process, the optical feedback term should be included. Also, the arrival time of the feedback pulses should be considered. Adding these factors to the rate equation A2 gives the desired rate equation for self-seeding as follows:

$$\frac{dS_i}{dt}=\Gamma v_g g_i S_i+\frac{\beta N}{\tau_s}-\frac{S_i}{\tau_p}+\frac{1}{2}\alpha_m v_g \kappa S_j(t-\tau_{ec})\delta_{ij} \tag{A3}$$

where κ is the effective cavity reflectivity which can control the amount of power fed back by the external mirror, δ is the function which select only one particular wavelength feedback into the laser diode. And the term $S(t-\tau)$ controls the feedback

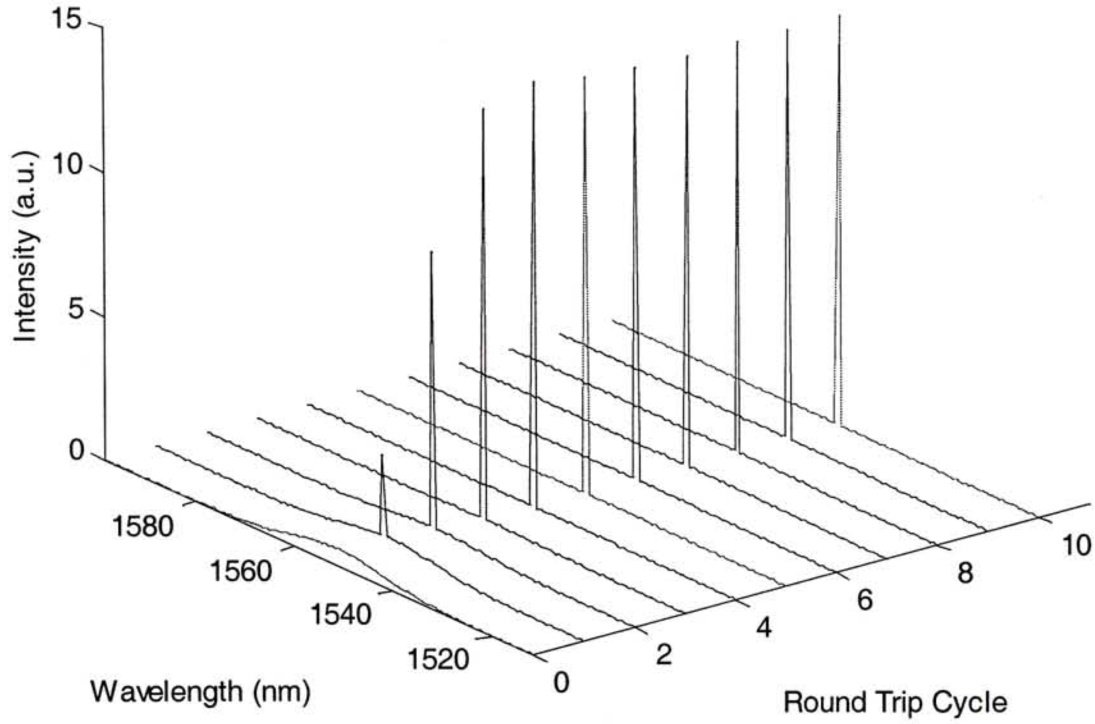

Fig. A1 *Modeling of spectral evolution of self-seeded Fabry-Perot laser diode near 1550 nm.*

pulse arrival time. Figure A1 shows the simulation result as the spectral characteristic of laser diode is changed by the reflected pulses. Stable output is obtained after four round-trip cycles, which shows well agreement with the result obtained from experiment in Chapter 3.

Reference

[1] Cheuk Wing Tung, "Analysis of optical feedback and injection in semiconductor lasers", Final Year Project, 2000.

Appendix C. List of Figures

CUHK Libraries
003803507